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FOR THE TECHNOLOGY INSIDER

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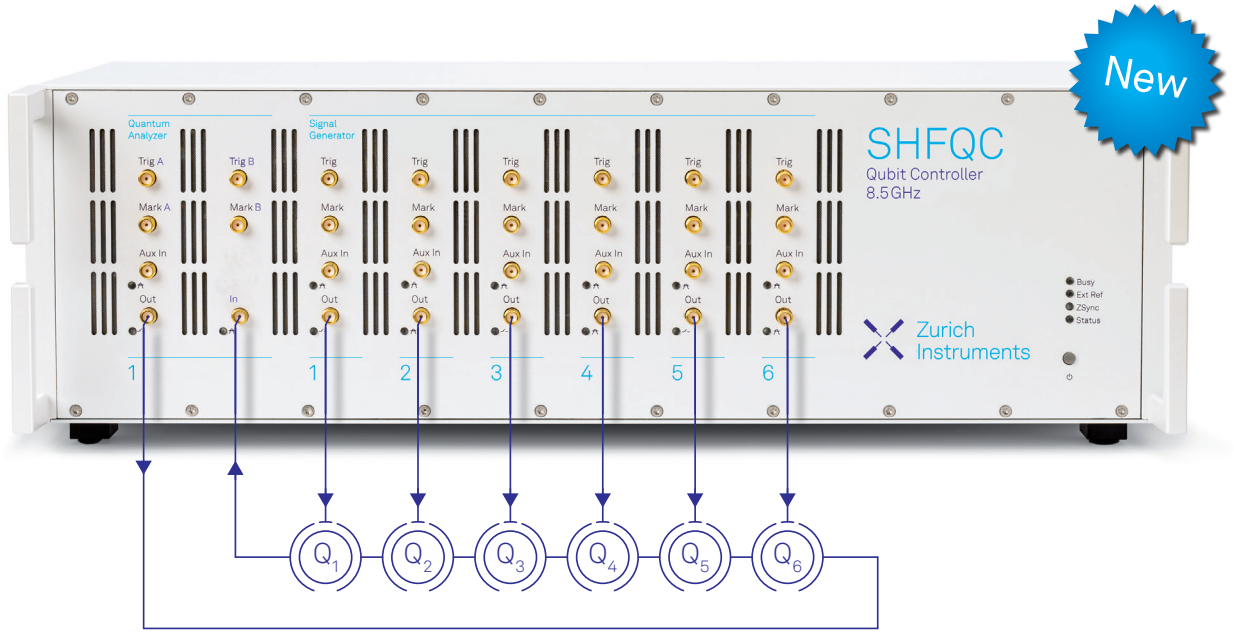

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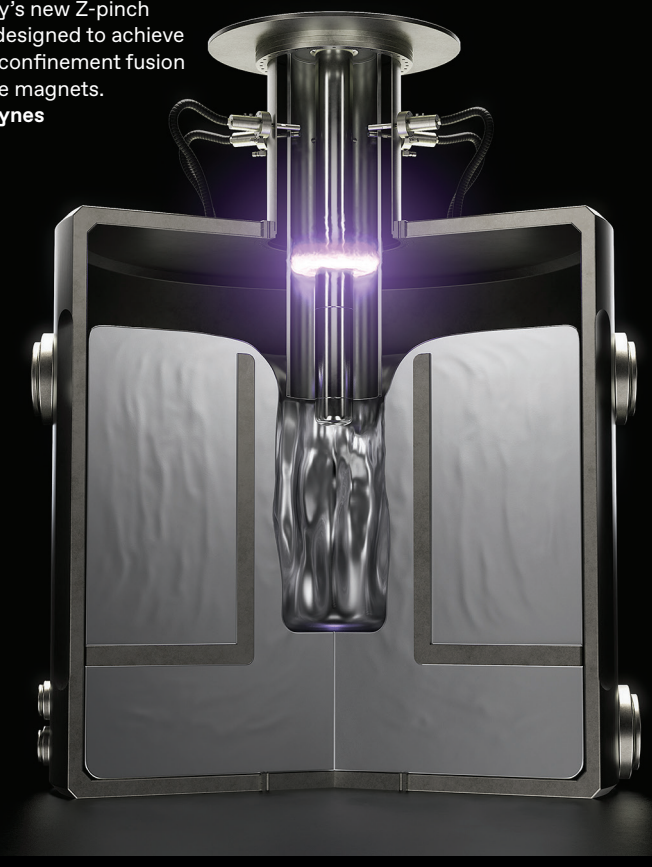

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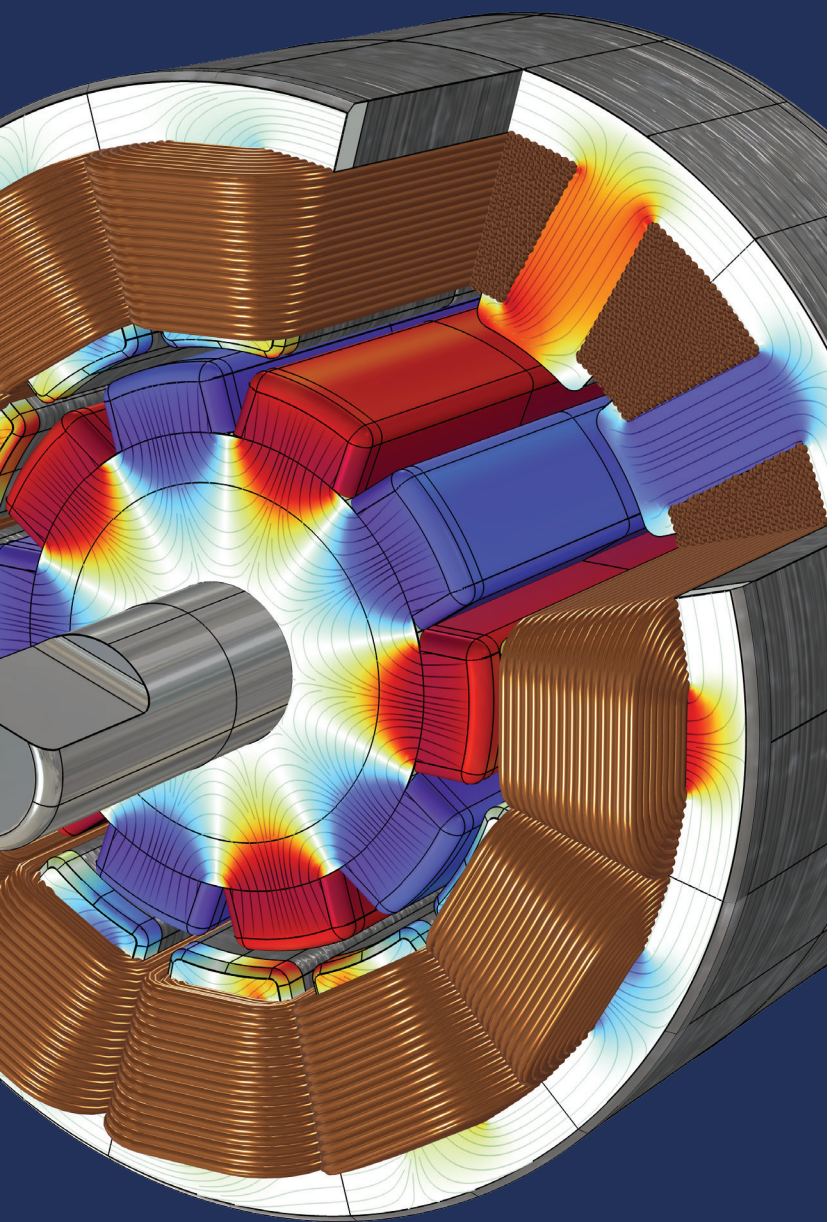

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IEEE

BACK STORY

Living in Color

The Barcelona-based illustrator Edmon de Haro [above] is known for his playful and dramatic photo collages, which combine simple images with vivid colors to convey often complex ideas. To see what we mean, take a look at his illustrations in this issue on pages 27, 42, and 47.

Given the bright hues in de Haro's work, you might be surprised to learn that de Haro is color-blind. "I have the most common type, red-green color-blindness, so I confuse those two colors," de Haro says. "But it's not as simple as that. I can confuse other colors, like pink for gray or green for brown. When colors are very dark or very pale, I can confuse them. If the red and green are next to each other, I may confuse them, but if they're separated by another color, it's usually okay."

To avoid any confusion, de Haro prefers to work with saturated colors—intense shades that pop off the page. "I need to be very sure of the color I'm using," he says. The color primarily serves as a backdrop for whatever object de Haro has chosen—a purse and some coins to illustrate an article on a new cryptocurrency wallet, for example. "Many people can use colors and be very precise in finding combinations that work together. For me, color is a more limited tool."

De Haro credits his mother for his artistic sensibility. "My mother studied art and wanted to be an illustrator, but she ended up teaching art in my school," he says. "In my memory, she's always drawing at the table. These days, she draws with an iPad."

De Haro has never viewed his color-blindness as an obstacle, perhaps because a number of members of his extended family share the same trait. A few of them even work in the visual arts. "We like to see each other's work, and we laugh a lot when we talk about color in our projects, because we know we're unusual in this respect," de Haro says. ■

ROGER DE HARO

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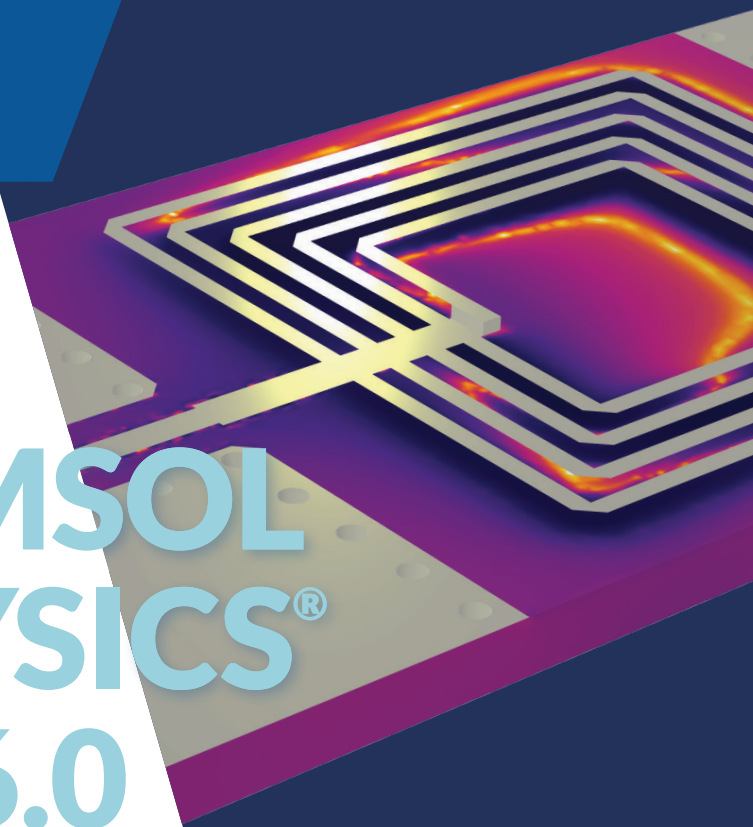

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TOM CLYNES

Clynes is a writer and photojournalist who covers science and the environment. In this issue, he reports on fusion startup Zap Energy [p. 54]. "Among the subjects I cover, the quest for viable fusion power continues to beguile—not least because it offers a potential solution to the problems that keep me awake at night worrying about my kids' future," Clynes says.

JEFF FOUST

Foust is a senior staff writer at *Space News*. In "NASA's Space Launch System Will Lift Off," he examines NASA's giant new booster, as well as those from Blue Origin and SpaceX [p. 36]. All three may see their first launches in 2022. "I was too young to see the legendary Saturn V launch," says Foust. "But I'm looking forward to seeing a new generation of giant rockets start flying in the next few years."

MARIA GALLUCCI

Gallucci, a longtime contributor to *IEEE Spectrum*, is a clean-energy reporter for Canary Media. On page 46, she looks at solar geoengineering, a controversial approach to mitigate climate change that's also discussed in Kim Stanley Robinson's 2020 novel *The Ministry for the Future*. In the novel, "after experiencing a massive deadly heat wave, the Indian government decides to perform solar geoengineering over the objections of other countries," Gallucci says. "And it all seemingly works out fine. That made me laugh out loud—if only it were so simple!"

PETER PALOMAKI

Palomaki is the owner and chief scientist of Palomaki Consulting, where he uses his expertise in materials chemistry to solve challenging problems in implementing quantum-dot technology. Palomaki has been known to frequent electronics stores with a spectrometer in hand to measure the optical output of the newest displays. When QD-OLED displays, which he writes about on page 52, make it to store shelves, he aims to be one of the first to get a glimpse and a measurement.

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Deep-sea nodules could supply the metals needed to make EV batteries for decades.

THE METALS COMPANY

SPECTRAL LINES

The Seabed Solution › After 150 years, is the time finally right for deep-ocean mining?

BY GLENN ZORPETTE

The three-year voyage of the HMS *Challenger* was one of the greatest scientific expeditions in an era with quite a few of them. The former warship departed England in 1872 with a complement of 237 on a mission to collect marine specimens and also to map and sample huge swaths of the seafloor.

The ship traveled 125,936 kilometers, and the mission succeeded beyond the wildest dreams of its backers. It discovered 4,700 new marine species, the Mid-Atlantic Ridge, and the Mariana Trench. Its bathymetric data, collected laboriously with a weighted line, was used to make the seafloor maps that guided the route of an early transatlantic telegraph cable. But the crew's most puzzling discovery was made on 18 February 1873, while dredging an abyssal plain near the Canary Islands. The dredging apparatus came up loaded with potato-size nodules; subsequent analysis found them to be rich in manganese, nickel, and iron. It was the first of many such hauls by the *Challenger* crew, from the Indian Ocean to the Pacific, where the dredges sometimes yielded a briny jumble of the dark-gray nodules, shark's teeth, and, oddly, whale ear bones.

Now, as David Schneider notes in "Deep-sea Mining Stirs Up Muddy Questions," on page 56, a Canadian firm called the Metals Company (formerly DeepGreen Metals) is poised to find out whether existing technology can be used to harvest those nodules and recover their metals at costs competitive with more traditional mining techniques. Over the next decade, a great shift to electric vehicles is expected to drive up demand for cobalt, nickel, copper, and manganese—all key metals in lithium-ion batteries, and all present in minable quantities in seafloor nodules.

It has been a long and twisty road from the initial discoveries by the *Challenger*. Nearly 90 years would go by before somebody would propose collecting the nodules on a mass scale. In the December 1960 issue of *Scientific American*, the mining engineer John L. Mero argued his case and triggered a substantial spending spree as oceanographic research institutes sought, successfully, to verify his claims.

Still, it would be another half century before a startup, Nautilus Minerals, would try to make a go of deep-seabed mining. Nautilus's idea wasn't to collect nodules, though, but rather to cut and drill into crusty deposits near deep-sea thermal vents, where valuable metals and minerals have been deposited over many millennia. But after raising some US $686 million, building three large undersea drilling robots, and securing a license to mine the seabed off Papua New Guinea, Nautilus went bankrupt in November 2019. When it ceased operations, it hadn't mined any metal ore at all.

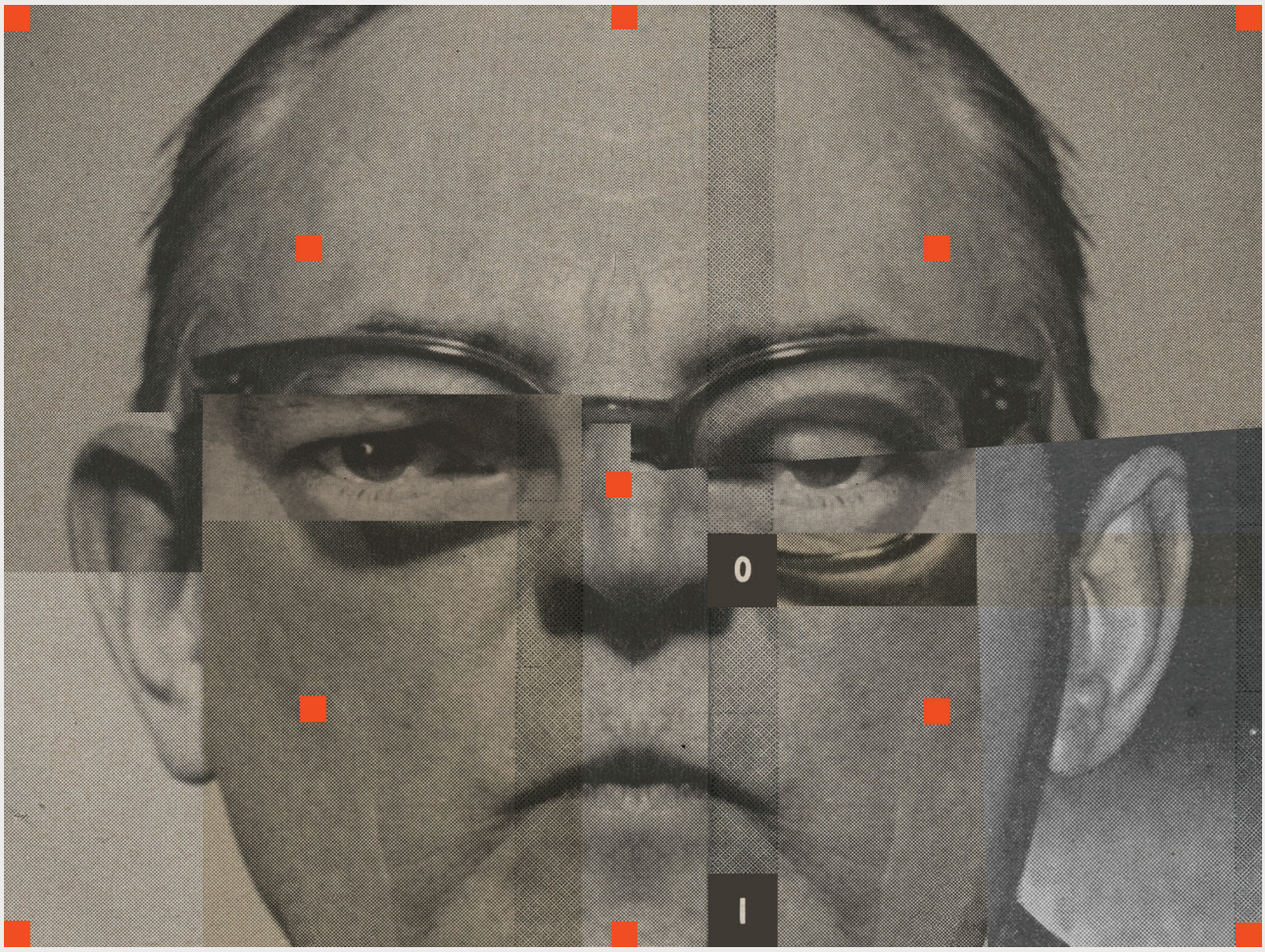
The Metals Company, too, faces headwinds. So far, the firm has negotiated exploration rights to three different regions in the Pacific totaling some 74,700 square kilometers of seabed. It's converting a 228-meter former drill ship into a mining-support surface ship, and it's now building a seafloor robot to suck up and collect nodules at depths exceeding 4,000 meters. The company has competition: Belgium-based Global Sea Mineral Resources is also testing a robotic undersea-nodule collector and has plans to mine the same region of the vast Pacific abyssal plains, called the Clarion-Clipperton Zone, as the Metals Company.

Conservationists are mobilizing against the plans. *The Atlantic*, *The Guardian*, and *Nature* have all published articles citing delicate marine ecosystems that could be threatened by the mining. At the same time, the International Energy Agency projects that 145 million electric vehicles will be on the road by 2030. Each one of them will have a battery containing quantities of cobalt, manganese, and nickel ranging from several kilograms to a couple of dozen kilograms each. The Metals Company claims that the metals content of the nodules in just its area of exploration in the Clarion Zone could supply 250 million EVs.

Analysts believe that conventional surface mines could supply that much metal, but digging it out of the ground would not be pretty. The mining of cobalt, lithium, manganese, and nickel have all long been associated with environmental and human-rights disasters.

Humanity has begun insisting on greater sustainability in countless industries. But in mining, at least, it may find the apt phrase is not so much "better angels" as "lesser evil." ■

News



ARTIFICIAL INTELLIGENCE

AI's Real Worst-Case Scenarios › Who needs Terminators when you have precision clickbait and ultra-deepfakes?

BY NATASHA BAJEMA

Hollywood's worst-case scenario involving artificial intelligence (AI) is as familiar as any trope in blockbuster movies: Machines acquire humanlike intelligence, achieving sentience, and inevitably turn into evil overlords that attempt to destroy the human race. This narrative capitalizes on our innate fear of technology, a reflection of the profound change that often accompanies new technological developments.

However, as Malcolm Murdock, machine-learning engineer and author of the 2019 novel *The Quantum Price,* puts it, "AI doesn't have to be sentient to kill

Photo-Illustration by Mike McQuade

us all. There are plenty of other scenarios that will wipe us out before sentient AI becomes a problem."

In interviews with AI experts, *IEEE Spectrum* has uncovered six real-world AI worst-case scenarios that are far more mundane than those depicted in the movies. But they're no less dystopian. And most don't require a malevolent dictator to bring them to full fruition. Rather, they could simply happen by default, unfolding naturally—that is, if nothing is done to stop them. To prevent these worst-case scenarios, we must abandon our pop-culture notions of AI and get serious about its unintended consequences.

1. When Fiction Defines Our Reality...

Unnecessary tragedy may strike if we allow fiction to define our reality. But what choice is there when we can't tell the difference between what is real and what is false in the digital world?

In a terrifying scenario, the rise of deepfakes—fake images, video, audio, and text generated with advanced machine-learning tools—may someday lead national-security decision-makers to take real-world action based on false information, leading to a major crisis, or worse yet, a war.

Andrew Lohn, senior fellow at Georgetown University's Center for Security and Emerging Technology (CSET), says that "AI-enabled systems are now capable of generating disinformation at [large scales]." By producing greater volumes and variety of fake messages, these systems can obfuscate their true nature and optimize for success, improving their desired impact over time.

The mere notion of deepfakes amid a crisis might also cause leaders to hesitate to act if the validity of information cannot be confirmed in a timely manner.

Marina Favaro, research fellow at the Institute for Research and Security Policy in Hamburg, Germany, notes that "deepfakes compromise our trust in information streams by default." Both action and inaction caused by deepfakes have the potential to produce disastrous consequences for the world.

"We are entering dangerous and uncharted territory with the rise of surveillance and tracking through data, and we have almost no understanding of the potential implications."

—ANDREW LOHN, GEORGETOWN UNIVERSITY

2. A Dangerous Race to the Bottom

When it comes to AI and national security, speed is both the point and the problem. Since AI-enabled systems confer greater speed benefits on its users, the first countries to develop military applications will gain a strategic advantage. But what design principles might be sacrificed in the process?

Things could unravel from the tiniest flaws in the system and be exploited by hackers. Helen Toner, director of strategy at CSET, suggests a crisis could "start off as an innocuous single point of failure that makes all communications go dark, causing people to panic and economic activity to come to a standstill. A persistent lack of information, followed by other miscalculations, might lead a situation to spiral out of control."

Vincent Boulanin, senior researcher at the Stockholm International Peace Research Institute (SIPRI), in Sweden, warns that major catastrophes can occur "when major powers cut corners in order to win the advantage of getting there first. If one country prioritizes speed over safety, testing, or human oversight, it will be a dangerous race to the bottom."

For example, national-security leaders may be tempted to delegate decisions of command and control, removing human oversight of machine-learning models that we don't fully understand, in order to gain a speed advantage. In such a scenario, even an automated launch of missile-defense systems initiated without human authorization could produce unintended escalation and lead to nuclear war.

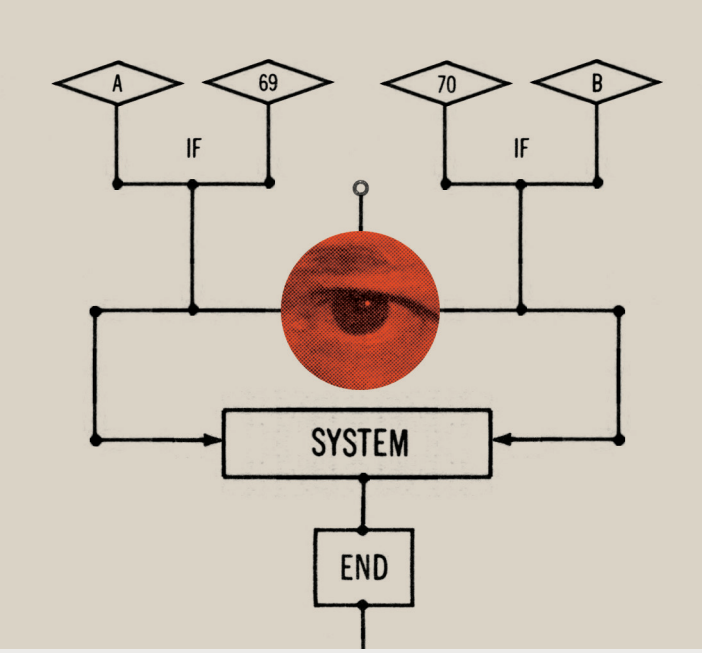
3. The End of Privacy and Free Will

With every digital action, we produce new data—emails, texts, downloads, purchases, posts, selfies, and GPS locations. By allowing companies and governments to have unrestricted access to this data, we are handing over the tools of surveillance and control.

With the addition of facial recognition, biometrics, genomic data, and AI-enabled predictive analysis, Lohn of CSET worries that "we are entering dangerous and uncharted territory with the rise of surveillance and tracking through data, and we have almost no understanding of the potential implications."

Michael C. Horowitz, director of Perry World House, at the University of Pennsylvania, warns "about the logic of AI and what it means for domestic repression. In the past, the ability of autocrats to repress their populations relied upon a large group of soldiers, some of whom may side with society and carry out a coup d'etat. AI could reduce these kinds of constraints."

The power of data, once collected and analyzed, extends far beyond the functions of monitoring and surveillance to allow for predictive control. Today, AI-enabled systems predict what products we'll purchase, what entertainment we'll watch, and what links we'll click. When these platforms know us far better than we know ourselves, we may not notice the slow creep that robs us of our



free will and subjects us to the control of external forces.

4. A Human Behavioral Experiment

The ability of children to delay immediate gratification, to wait for the second marshmallow, was once considered a major predictor of success in life. Soon even the second-marshmallow kids will succumb to the tantalizing conditioning of engagement-based algorithms.

Social media users have become rats in lab experiments, living in human Skinner boxes, glued to the screens of their smartphones, compelled to sacrifice more precious time and attention to platforms that profit from it at their expense.

Helen Toner of CSET says that "algorithms are optimized to keep users on the platform as long as possible." By offering rewards in the form of likes, comments, and follows, Malcolm Murdock explains, "the algorithms short-circuit the way our brain works, making our next bit of engagement irresistible."

To maximize advertising profit, companies steal our attention away from our jobs, families and friends, responsibilities, and even our hobbies. To make matters worse, the content often makes us feel miserable and worse off than before. Toner warns that "the more time we spend on these platforms, the less time we spend in the pursuit of positive, productive, and fulfilling lives."

5. The Tyranny of AI Design

Every day, we turn over more of our daily lives to AI-enabled machines. This is problematic since, as Horowitz observes, "we have yet to fully wrap our heads around the problem of bias in AI. Even with the best intentions, the design of AI-enabled systems, both the training data and the mathematical models, reflects the narrow experiences and interests of the biased people who program them. And we all have our biases."

As a result, Lydia Kostopoulos, senior vice president of emerging tech insights at the Clearwater, Fla.–based IT security company KnowBe4, argues that "many AI-enabled systems fail to take into account the diverse experiences and characteristics of different people." Since AI solves problems based on biased perspectives and data rather than the unique needs of every individual, such systems produce a level of conformity that doesn't exist in human society.

Even before the rise of AI, the design of common objects in our daily lives has often catered to a particular type of person. For example, studies have shown that cars, hand-held tools including cellphones, and even the temperature settings in office environments have been established to suit the average-size man, putting people of varying sizes and body types, including women, at a major disadvantage and sometimes at greater risk to their lives.

When individuals who fall outside of the biased norm are neglected, marginalized, and excluded, AI turns into a Kafkaesque gatekeeper, denying access to customer service, jobs, health care, and much more. AI design decisions can restrain people rather than liberate them from day-to-day concerns. And these choices can also transform some of the worst human prejudices into racist and sexist hiring and mortgage practices, as well as deeply flawed and biased sentencing outcomes.

6. Fear of AI Robs Humanity of Its Benefits

Since AI's capabilities of course scale with the computing power and complexity of the hardware it runs on, societal fears around AI seem poised only to grow over time. "Artificial neural networks can do insanely powerful things," said Murdock, "and we need to be prudent about the risks." But what if people become so afraid of AI that governments regulate it in ways that rob humanity of AI's many benefits? For example, DeepMind's AlphaFold program achieved a major breakthrough in predicting how amino acids fold into proteins, making it possible for scientists to identify the structure of 98.5 percent of human proteins. This milestone will provide a fruitful foundation for the rapid advancement of the life sciences. Consider the benefits of improved communication and cross-cultural understanding made possible by seamlessly translating across any combination of human languages, or the use of AI-enabled systems to identify new treatments and cures for disease. Knee-jerk regulatory actions by governments to protect against AI's worst-case scenarios could also backfire and produce their own unintended negative consequences, in which we become so scared of the power of this tremendous technology that we resist harnessing it for the actual good it can do in the world. ■

Photo-Illustration by Mike McQuade

Microsoft's office in Beijing houses a company division that trained many of China's present-day AI and technology-industry titans.

NG HAN GUAN/AP

TECH POLICY

U.S.-China Rivalry Boosts Tech—and Tensions ›

One-upmanship can even be productive, until militaries get involved

BY CRAIG S. SMITH

In June 2020, OpenAI, an independent artificial-intelligence research lab based in San Francisco, announced GPT-3, the third generation of its massive Generative Pre-trained Transformer language model, which can write everything from computer code to poetry.

A year later, with much less fanfare, Tsinghua University's Beijing Academy of Artificial Intelligence released an even larger model, Wu Dao 2.0, with 10 times as many parameters—the neural network values that encode information. While GPT-3 boasts 175 billion parameters, Wu Dao 2.0 has a whopping 1.75 trillion—though not directly comparable. Moreover, the model is capable not only of generating text like GPT-3 does but also images from textual descriptions like OpenAI's 12-billion-parameter DALL-E model, and has a scaling strategy similar to Google's 1.6-trillion-parameter Switch Transformer model.

Tang Jie, the Tsinghua University professor leading the Wu Dao project, said in a recent interview that the group built an even bigger, 100-trillion-parameter model in June, though they have not trained it to "convergence," the point at which the model stops improving. "We just wanted to prove that we have the ability to do that," Tang said.

This isn't simple one-upmanship. On the one hand, it's how research progresses. But on the other, it is emblematic of an intensifying competition between the world's two technology superpowers. Whether the researchers involved like it or not, their governments are eager to adopt each AI advance into their national-security infrastructure and military capabilities.

That matters, because dominance in the technology surely improves the odds of victory in any future war. Such an advantage also likely guarantees the longevity and global influence of the government that wields it. Already, China is exporting its AI-enabled surveillance technology—which can be used to quash dissent—to client states and is espousing an authoritarian model that promises economic prosperity as a counter to democracy, something that the Soviet Union was never able to do.

Ironically, China is a competitor that the United States abetted. It's well known that the U.S. consumer market fed China's export engine, itself outfitted with U.S. machines, and led to the fastest-growing economy in the world since the 1980s. What's less well-known is how a handful of technology companies transferred

the know-how and trained the experts now giving the United States a run for its money in AI.

Blame Bill Gates, for one. In 1992, Gates led Microsoft into China's fledgling software market. Six years later, he established Microsoft Research Asia, the company's largest basic and applied computer-research institute outside the United States. People from that organization have gone on to found or lead many of China's top technology institutions.

For instance, in 2012 Zhang Yiming, a Microsoft Research Asia alum, founded the video-sharing platform's parent company, ByteDance, developer and operator of the social media platform TikTok. He hired a former head of Microsoft Research Asia, Zhang Hongjiang, to lead ByteDance's Technical Strategy Research Center. This Zhang is now head of the Beijing Academy— the organization behind Wu Dao 2.0, currently the largest AI system on the planet. That back-and-forth worries U.S. national-security strategists, who plan for a day when researchers and companies are forced to take sides.

Today's competition has roots in an incident on 7 May 1999, when a U.S. B-2 Stealth Bomber dropped bombs on the Chinese embassy in Belgrade, Serbia, killing three people.

"That's when the Chinese started saying, 'We're moving beyond attrition warfare' to what they referred to as systems confrontation, the confrontation between their operational system and the American operational system," says Robert O. Work, former U.S. Deputy Secretary of Defense and vice chairman of the recently concluded National Security Commission on Artificial Intelligence. "Their theory of victory is what they refer to as system destruction."

China's "theory of victory is what they refer to as system destruction."

—ROBERT O. WORK, FORMER U.S. DEPUTY SECRETARY OF DEFENSE

System-destruction warfare is part and parcel of what the People's Liberation Army thinks of as "intelligentized" warfare, in which war is waged not only in the traditional physical domains of land, sea, and air but also in outer space, nonphysical cyberspace, and electromagnetic and even psychological domains—all enabled and coordinated with AI.

Work says the first major U.S. AI effort toward intelligentized warfare was to use computer vision to analyze thousands of hours of full-motion video being downloaded from dozens of drones. Today, that effort, dubbed Project Maven, detects, classifies, and tracks objects within video images, and it has been extended to acoustic data and signals intelligence.

The Chinese have kept pace. China is actively pursuing AI-based target recognition and automatic-weapon-firing research, which could be used in lethal autonomous weapons. Meanwhile, according to Work, the country's swarm technology may be ahead of the United States—whose military budget, nevertheless, is three times that of China.

Chinese firm Baidu—whose comparatively modest Sunnyvale, Calif., office is pictured here in 2018—is one of the largest Internet companies in the world.

"I worry about their emphasis on swarms of unmanned systems," says Work, adding that the Chinese want to train swarms of a hundred vehicles or more, including underwater systems, to coordinate navigation through complex environments. "While we also test swarms, we have yet to demonstrate the ability to employ these types of swarms in a combat scenario."

This type of research and testing has prompted calls for preemptive bans on lethal autonomous weapons, but neither country is willing to declare an outright prohibition. Barring a prohibition, many people believe that China and the United States, along with other countries, should begin negotiating an arms-control agreement banning the development of systems that could autonomously order a preemptive or retaliatory attack. Such systems might inadvertently lead to "flash wars," just as AI-driven autonomous trading has led to flash crashes in the financial markets.

"Neither of us wants to get into a war because an autonomous-control system made a mistake and ordered a preemptive strike," Work says, referring to the United States and China.

All of this contributes to a dilemma facing the twin realms of AI research and military modernization. The international research community, collaborative and collegial, prefers to look the other way and insist that it only serves the interest of science. But the governments that fund that research have clear agendas, and military enhancement is undeniably one.

Geoffrey Hinton, regarded as one of the godfathers of deep learning, the kind of AI transforming militaries today, left the United States and moved to Canada largely because he didn't want to depend on funding from the Defense Advanced Research Projects Agency, or DARPA. The agency, the largest funder of AI research in the world, is responsible for the development of emerging technologies for military use.

Hinton instead helped to put deep learning on the map in 2012 with a

SMITH COLLECTION/GADO/GETTY IMAGES

now-famous neural net called AlexNet when he was at the University of Toronto. But Hinton was also in close contact with the Microsoft Research Lab in Redmond, Wash., before and after his group validated AlexNet, according to one of Hinton's associates there, Li Deng, then principal researcher and manager and later chief scientist of AI at Microsoft. When Hinton achieved his 2012 breakthrough, news soon spread through Microsoft's Chinese brain trust to China.

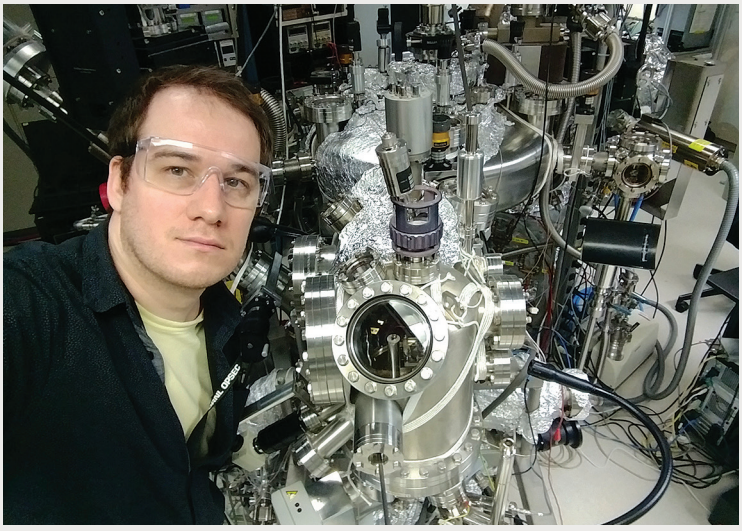
The United States has since tried to limit this cross-pollination, barring Chinese nationals known to have worked for China's military or intelligence organizations from working with U.S. research institutions. But research continues to flow back and forth between the two countries: Microsoft maintains its research lab in Beijing, and the Chinese Internet and AI giant Baidu has a research lab in Silicon Valley, for example.

Tsinghua University's Tang said decoupling the two countries would slow China's AI research—not because it would stop the flow of ideas, but because it would cut China off from the advanced semiconductors needed to train AI models. "We hope that we can do science for the world, not just the one country," Tang says. But, he added, "we should do something on demand based on the national project research plan."

China's National Intelligence Law compels its companies and researchers to cooperate when asked. China began pouring billions of dollars into AI research in 2017, and among the organizations set up with that funding was Tsinghua's Beijing Academy, where Tang and his team built Wu Dao 2.0.

By most metrics, Wu Dao 2.0 has surpassed OpenAI's GPT-3. Tang says it was trained on 4.9 terabytes of clean data, including Chinese-language text, English-language text, and images. OpenAI has said that GPT-3 was trained on just 570 gigabytes of clean, primarily English-language text.

Tang says his group is now working on video with the goal of generating realistic video from text descriptions. "Hopefully, we can make this model do something beyond the Turing test," he says, referring to an assessment of whether a computer can generate text indistinguishable from that created by a human. "That's our final goal." ■



MAXIM ZIATDINOV

Maxim Ziatdinov of Oak Ridge National Laboratory sees automated microscopy ultimately becoming a crucial tool for next-generation quantum computers.

MICROSCOPY

Navigating the Nanoscale ›

Deep learning enables push toward self-driving microscopes

BY DAN GARISTO

It's difficult to find an area of scientific research where deep learning isn't discussed as the next big thing. Claims abound: Deep learning will spot cancers; it will unravel complex protein structures; it will reveal new exoplanets in previously analyzed data; it will even discover a theory of everything. Knowing what's real and what's just hype isn't always easy.

One promising—perhaps even overlooked—area of research for deep learning to make its mark is in microscopy. In spite of new discoveries, the underlying workflow of techniques like scanning probe microscopy (SPM) and scanning transmission electron microscopy (STEM) has remained largely unchanged for decades. Skilled human operators must painstakingly set up, observe, and analyze samples. Deep learning has the potential not only to automate many of the tedious tasks, but also to dramatically speed up the analysis time by honing in on microscopic features of interest.

"People usually just look at the image and identify a few properties of interest," says Maxim Ziatdinov, a researcher at Oak Ridge National Laboratory. "They basically discard most of the information because there is just no way to actually extract all the features of interest from the data." With deep learning, Ziatdinov says, it's possible to extract information about the position and type of atomic structures in seconds, opening up a vista of possibilities.

It's a twist on the classical dream of doing more with smaller things (most famously expressed in Richard Feynman's "There's Plenty of Room at the Bottom"). Improving hardware isn't the only way to increase the functionality of micro-

scopes. Software can play a role, too—by making a microscope autonomous. "Such a machine will 'understand' what it is looking at and automatically document features of interest," an article in the *Materials Research Society Bulletin* declared. "The microscope will know what various features look like by referencing databases or can be shown examples on the fly."

Despite the "micro-" prefix, microscopy such as SPM and STEM actually deals with objects on the nanoscale, including individual atoms. In SPM, a nanoscale tip hovers over the sample surface and traces its grooves, like the needle of a record player, to create an image. On the other hand, STEM generates an image by showering a sample with electrons and collecting those that pass through, essentially creating a negative.

Both microscopy techniques allow researchers to quickly observe the broad structural features of a sample. Researchers like Ziatdinov are interested in the functional properties of certain features such as defects. By applying a stimulus like an electric field to the sample, they can measure how it responds and build a functional map, too.

But zooming in on a structural image to gather functional data is time-prohibitive, and human operators have to make a guess about which features they choose to analyze. There hasn't been a rigorous way to predict functionality from structure, so operators have simply had to get a knack for picking good features.

The hope is that this tedious feature-picking can be outsourced to a neural network that predicts features of interest and navigates to them, dramatically speeding up the process.

Automated microscopy is still at the proof-of-concept stage, with a few groups of researchers around the world hammering out the principles and doing preliminary tests. Unlike many areas of deep learning, success here would not be simply automating preexisting measurements; with automation, researchers could make measurements that have been inaccessible.

Ziatdinov and his colleagues have already made some progress toward such a future. For years, they sat on microscopy data of graphene—a few frames showing a defect that created strain in the atomically thin material. "We couldn't analyze it, because there's just no way that you can extract positions of all the atoms," Ziatdinov says. But by training a neural net on the graphene, they were able to categorize new structures on the edges of defects.

Microscopy isn't just limited to observing. By blasting samples with a high-energy electron beam, researchers can shift the position of atoms, effectively creating an "atomic forge." As with a conventional billows-and-iron forge, automation could make things a lot easier. An atomic forge guided by deep learning could spot defects and fix them, or nudge atoms into place to form intricate structures—around the clock, without human error, sweat, or tears.

"If you actually want to have a manufacturing capability, just like with any other kind of manufacturing, you need to be able to automate it," Ziatdinov says.

Ziatdinov is particularly interested in applying automated microscopy to quantum devices, like topological qubits. Efforts to create these qubits have not proved successful, but he thinks he might have the answer. By training a neural network to understand the functions associated with specific features, deep learning could unlock what atomic tweaks are needed to create a topological qubit—something humans clearly haven't quite figured out.

Benchmarking exactly how far we are from a future where autonomous microscopy helps build quantum devices isn't easy. There are only a few human operators in the entire world, so it's difficult to compare deep-learning results to a human average. It's also unclear which obstacles will pose the biggest problems moving forward in a domain where the difference of a few atoms can be decisive.

The conclusion of a recent review of the prospects of autonomous microscopy argues it "will enable fundamentally new opportunities and paradigms for scientific discovery," with the caveat that "this process is likely to be highly nontrivial." Whether deep learning lives up to its promise on the microscopic frontier remains, literally, to be seen. ■

JOURNAL WATCH

This RISC-V Powerhouse Goes Light on the Power

As society's insatiable demand for computing power continues to grow, so too does the need for more efficient processors. A group of researchers in Switzerland has devised a new processor design that may help. It is physically small and computationally agile—and aptly named Snitch. (Harry Potter fans will get the reference.)

Florian Zaruba, a postdoc at the Integrated Systems Laboratory at the Swiss Federal Institute of Technology (ETH), in Zurich—and a researcher involved in the creation of Snitch—notes that commercial, general-purpose cores today rely on larger and more energy-hungry processors. "Snitch is the opposite," he says.

Typically, processors try to find an efficient instruction order on the fly, which requires additional hardware and thus uses more power. But Snitch is able to execute the majority of its basic instructions instantaneously, bypassing the need for this extra, burdensome hardware.

Zaruba and his colleagues describe their streamlined, RISC-V chip design in a study published 7 October in *IEEE Transactions on Computers*. They found that a single Snitch processor with its custom extensions was twice as energy efficient as comparable benchmark CPUs. When multiple processors were used in parallel, Snitch proved to be 3.5 times as energy efficient and up to six times as fast as the others.

The researchers have open-sourced Snitch's hardware design and note that they have seen growing interest from industry consortia, for example from the Open Hardware Group, in supporting commercialization efforts. —Michelle Hampson

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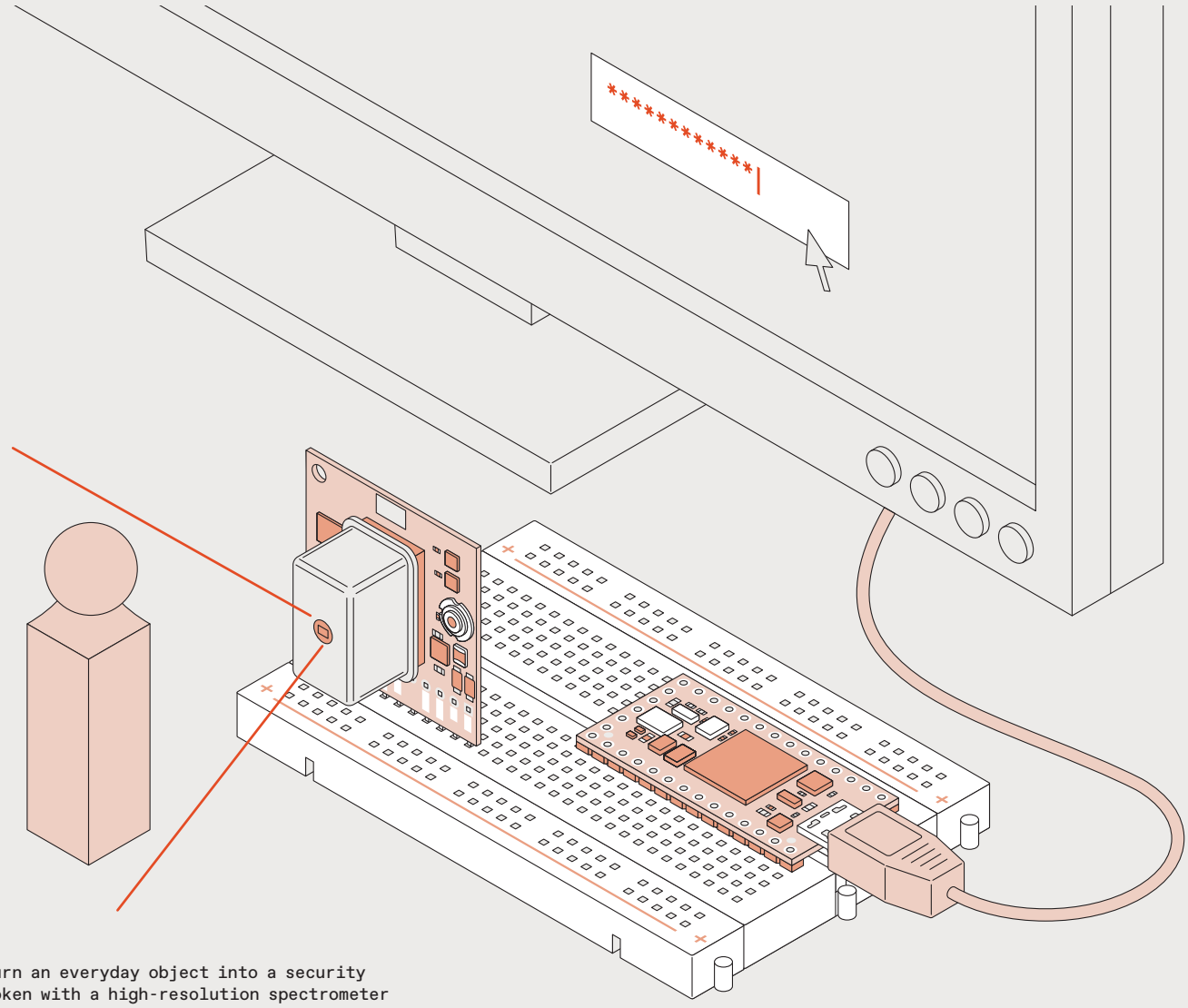
Hands On



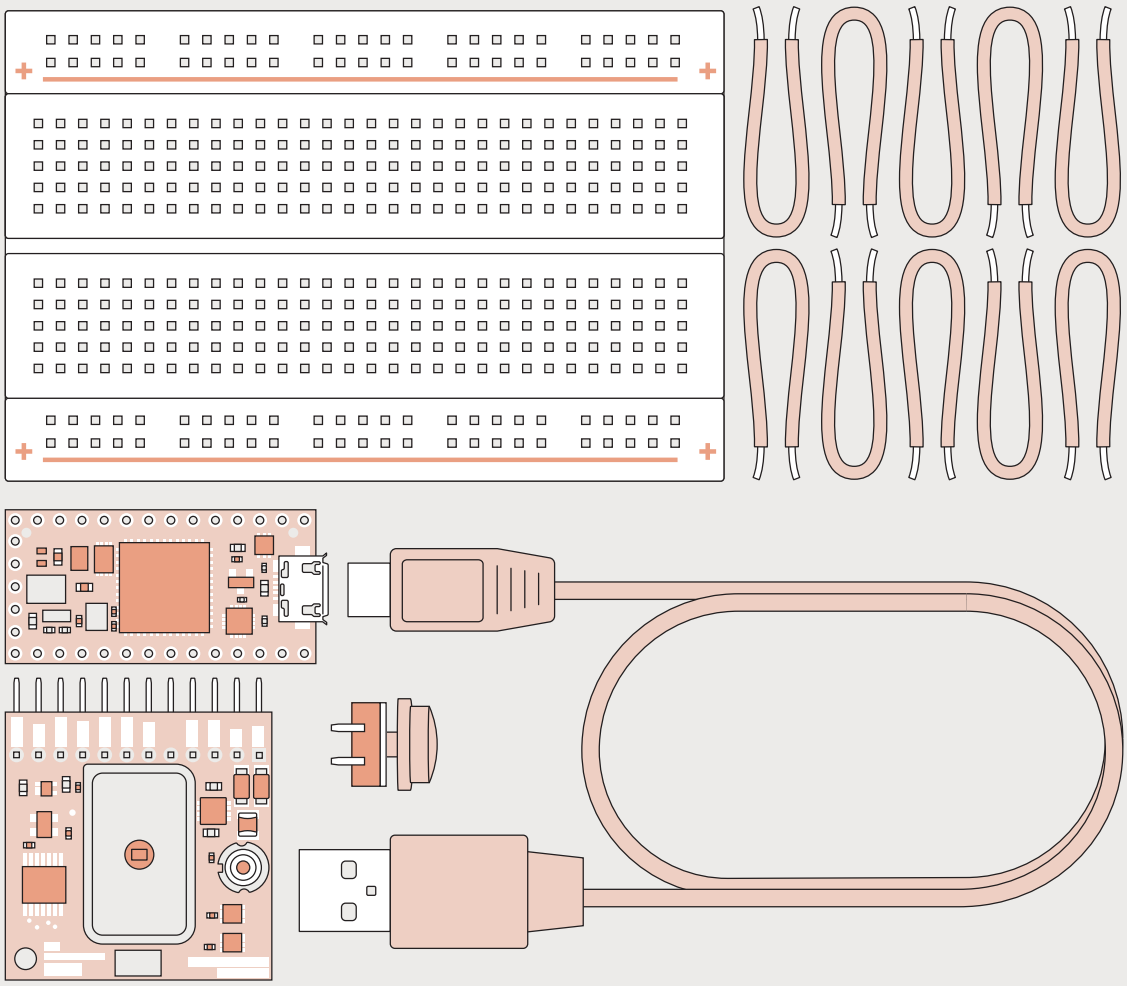
Turn an everyday object into a security token with a high-resolution spectrometer and a USB-enabled microcontroller.

My Password Is: [redacted] › Security with a high-resolution spectrometer

BY JEREMY S. COOK

My editor at *IEEE Spectrum* is convinced that in the future smartphones will have spectrometers to probe the world around them *[True-Ed.]*. As an experimental preview into this era, he obtained a spectrometer with a higher resolution than budget-minded makers have access to today, the Hamamatsu C12880MA, available in small quantities as a US $350

Illustrations by James Provost



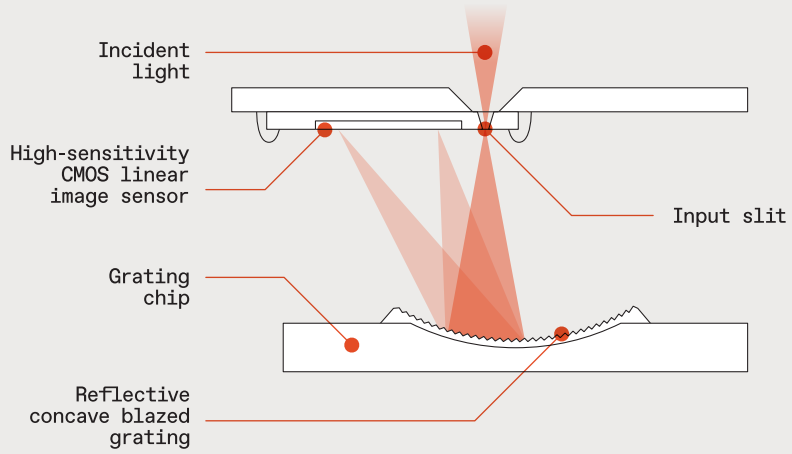
Only a few components are needed for my security prototype: a USB cable to send a password to the computer, the breakout board housing the spectrometer, a Teensy 4.0 microcontroller, an activation button, and a breadboard and jumper wires.

breakout board on Tindie. My part of the experiment? To see what idea the device would spark in me for a consumer-focused application.

As a bit of background, this spectrometer measures largely visible wavelengths of light and some in the infrared. It breaks out the light into a spectrum of varying intensity, which tells us more about a substance than we'd be able to sense by eyesight (or camera sight) alone. It has 288 individual pixels, which together can sense wavelengths of between 340 to 850 nanometers, with a resolution of 15 nm. This allows for much finer discrimination of spectra than you'd get from a typical $16 maker-grade spectrometer, sensitive to a relatively few distinct frequency bands.

So what use might a spectrometer be to a smartphone? What if it could be used to unlock the phone by scanning, say, one's skin tone—or rather, personal spectral signature? As of now though, the spectrometer—at 20.1 by 12.5 by 10.1 millimeters—is quite small, but not *quite* appropriate for today's ultrathin handsets. So I decided to prototype my phone idea by making a password-entry device for my laptop PC that would unlock it when I held my arm up to the sensor.

For my prototype, I plugged the spectrometer breakout board into a small breadboard, along with a Start button



The spectrometer works by passing light through a slit and then bouncing the light off a concave grating: Different frequencies of light illuminate different pixels on the striplike image sensor.

and the extremely capable Arm Cortex–based Teensy 4.0. The makers of the breakout board had already tested it with a Teensy, and the Teensy also has the advantage of having built-in USB HID (human interface device) capabilities, allowing it to emulate a keyboard when plugged into a computer.

The plan was that once the button is pressed, the Teensy would trigger an LED on the spectrometer breakout to provide consistent illumination. It would then read and parse the output from the spectrometer. If the spectrum matched that of a previously registered object, the Teensy would then automatically "type" my password, granting access to the computer.

Once I'd tested my sensor/microcontroller setup via the example code found online, the next question was whether or not such a device could send a string of text and actually be granted access to my MacBook computer. This actually turned out to be quite simple with the Teensy board, demonstrated via code from the USB_Keyboard Buttons example provided by the manufacturer of the Teensy. By modifying the text output initiated after a button press, it can send a stored password. Using Keyboard.println normally advances to the next line after text is entered, but it also duplicated the effect of pressing the Enter key in the password-entry box.

Now I needed to set things up so that the password was sent only when wavelength readings from the spectrometer matched up to the correct spectral signature.

I soon realized skin tone wasn't a good idea. Bodies are irregular, making consistent illumination hard, and many people have a similar skin tone to others. And what if I were to measure my skin after too much sun exposure, drinking a lot of water, or other conditions that could alter it's signature? These were complications that I wasn't keen on dealing with, though they might be trivial for a multibillion-dollar phone manufacturer.

This demo uses a high-resolution $350 spectrometer that's probably too pricey for a casual project today, but gives you a taste of the future.

For my prototype, I needed an inanimate object to act as a token instead. Something flat that could be positioned at a set distance to the sensor to return consistent spectral intensities, and possessing a distinctive color. It would also have to be something I'd consistently have on my person... Yes, I'm describing using a cellphone case as the password object, turning the concept of security *for* your phone on its head.

With the case at a distance of roughly 40 mm from the sensor, I started taking readings to determine its spectral signature. But the readings were inconsistent, especially just after the phone case was initially presented to the sensor aperture. The solution was to take multiple readings back-to-back, throw out the first four, and use the fifth as the actual input.

Looking at the results, I realized I didn't need to try to analyze and compare the entire spectrum. I could pick two notable peaks, and look at the intensities there. So I averaged the output from pixels 50 to 55, along with pixels 150 to 155. The results centered around an intensity count of 495 for the first peak and 315 for the second, based on an integration time of a few microseconds.

Of course, it would be very rare for the measured spectrum of the case to produce intensities counts that were both exactly 495 and 315, so I was caught in the classic security conundrum—how much leeway did I allow to prevent false-negative lockouts without making the setting so lax I would get false-positive access from incorrect objects? Eventually, with some trial and error, I settled on plus or minus 20 points. Now, when the button is pressed, a spectral reading is taken, compared, and if both values are within range, it enters the programmed password. (I should also note that if you happen to have a word processor or other text editor open and trigger the device, your password would be typed in to be on display for all to see!)

Code for this device is found in my GitHub repository, which is a modified version of the example code I referred to earlier. My setup should be fairly easy to duplicate and put into a permanent housing, though the spectrometer is admittedly pricey. Until, at least, Samsung or Apple starts churning spectrometers out by the million. ■

Illustration by James Provost

Q&A

TIM WEGNER/LAIF/REDUX

Lessons From a Second Life

› Before Meta, Philip Rosedale created an online universe

BY EDD GENT

When Mark Zuckerberg announced that Meta, née Facebook, would focus on building a shared virtual reality inspired by the fictional metaverse, many were reminded of Linden Lab's Second Life. This came to global prominence in the 2000s as an online world that users could explore, trade, and create in through avatars. (The IEEE even had its own virtual meeting space inside.) But although a dedicated group still populates Second Life, it faded from the zeitgeist.

Second Life's chief architect was Philip Rosedale, who left Linden Lab in 2010. He now runs a startup called High Fidelity, which, after some early virtual reality experiments, now develops spatial audio technology. *IEEE Spectrum* spoke with him to find out the challenges involved in building a virtual world and his insights for the latest pretenders to the metaverse crown. The conversation has been edited for length and clarity.

Second Life was almost like a proto-metaverse. Why do you think it didn't break through to the mainstream?

Philip Rosedale: It's interesting to note that Second Life is, in my opinion, still the largest and the closest thing to a metaverse that we have.... If you talk about people wanting to go to a live concert, or wanting to go shopping or something like that, I think Second Life is still US $650 million a year in transactions and a million people using it.... But as you say, it didn't break out, it didn't become a billion people.

I think the reason why it didn't, and this reason is still very true today, is simply that most adults are not yet comfortable engaging with new people, or engaging socially, in a multiplayer context online.... People are not able to communicate with facial and body language yet, in a way that is anywhere near adequate.... Nothing that Facebook has said or demonstrated changes what I just said.

VR adoption has always lagged expectations. Do you see any reason why that might be different this time around?

P.R.: In a word, no. I don't see a magic, new thing. I hoped that the VR headsets would be that. And that's why we raised so much money, hired so many people, and did so much work on that in the first stage of High Fidelity. But I do think that the technical problems in front of us around comfort, typing speed, and then communicating comfortably with others are still very daunting. And so I don't think there's anything new.

Another [issue] would be user-generated content. For any of these metaverse ideas to pan out, the content, the avatars, the buildings, the experiences, the games—they need to be entirely buildable by a really large number of people in much the same way that websites were buildable in parallel by a lot of people at once. We have to do the same thing with the metaverse, and there are not, as yet, toolkits and systems that would enable that.

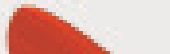
That definitely seems like a hard requirement to get anything near the scale of the Internet. If you actually want to build a multibillion-scale virtual world, everyone will have to somehow work in parallel. To get all those spaces up, the idea that it would all be done by one company like Facebook or Google or Apple seems completely impractical.

The second thing is, I'm really concerned that—and I said this all along with Second Life too, so my tone hasn't changed on this—any single-company, advertising-based, attention-based strategy for building virtual spaces would potentially be extremely damaging to people. I have become much more concerned than I was before. I think that we just didn't think about all the things that could go wrong 20 years ago. But now with the benefit of hindsight it's more obvious what we need to be concerned about. ■

Crosstalk

Extreme Designs

From the pyramids to the Hummer, more is often less



There is a fundamental difference between what can be designed and built and what makes sense. History provides a lesson in the shape of record-setting behemoths that have never since been equaled.

The Egyptian pyramids started small, and in just a few generations, some 4,500 years ago, there came Khufu's enormous pyramid, which nobody has ever tried to surpass. Shipbuilders in ancient Greece kept on expanding the size of their oared vessels until they built, during the third century B.C.E, a *tessarakonteres*, with 4,000 oarsmen. That vessel was too heavy, too ponderous, and therefore a naval failure. And architect Filippo Brunelleschi's vast cupola for Florence's Cathedral of Santa Maria del Fiore, built without scaffolding and finished in 1436, was never replicated.

The modern era has no shortage of such obvious overshoots. The boom in oil consumption following the Second World War led to ever-larger oil tankers, with sizes rising from 50,000 to 100,000 and 250,000 deadweight tonnes (dwt). Seven tankers exceeded 500,000 dwt, but their lives were short, and nobody has built a million-dwt tanker. Technically, it would have been possible, but such a ship would not fit through the Suez or Panama canals, and its draft would limit its operation to just a few ports.

The economy-class-only configuration of the Airbus A380 airliner was certified to carry up to 853 passengers, but it has not been a success. In 2021, just 16 years after it entered service, the last plane was delivered, a very truncated lifespan. Compare it with the hardly puny Boeing 747, which will see its final delivery in 2022—53 years after the plane's first flight, an almost human longevity. Clearly, the 747 was the right-sized record-breaker.

853
The most passengers on an airliner (Airbus A380)

Of course, the most infamous overshoot of all airplane designs was Howard Hughes's H-4 Hercules, dubbed the "Spruce Goose," the largest plane ever made out of wood. It had a wingspan of nearly 100 meters, and it was propelled by eight reciprocating engines, but it became airborne only once, for less than a minute, on 2 November 1947, with Hughes himself at the controls.

Another right-size giant is Ford's heavy and powerful F-150, now in its 14th generation: In the United States, it has been the bestselling pickup since 1977 and the best-selling vehicle since 1981. In contrast, the Hummer, a civilian version of a military assault vehicle, had a brief career but is now being resurrected in an even heavier electric version: The largest version using an internal combustion engine, the H1, weighed nearly 3.5 tonnes, the electric Hummer, 4.1 tonnes. I doubt we will see 14 generations of this beast.

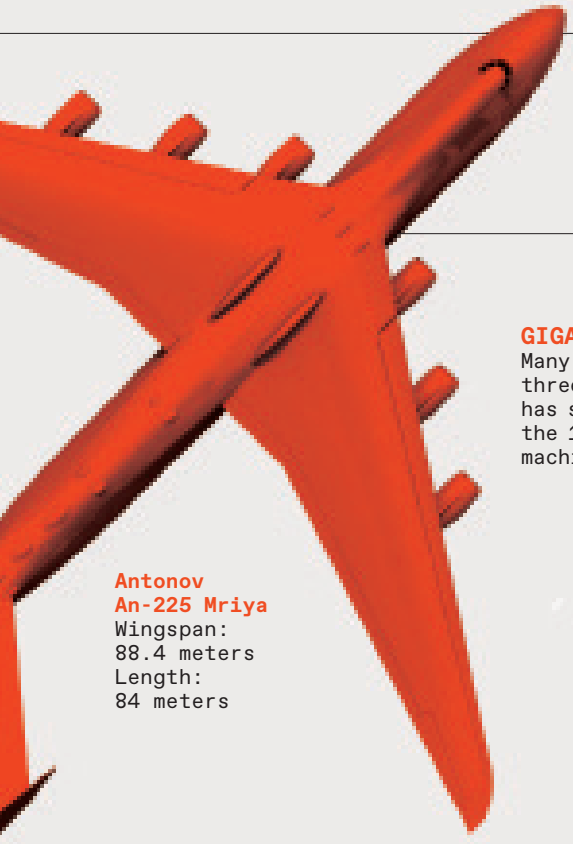
But these lessons of excess carry little weight with designers and promoters pursuing record sizes. Architects discuss buildings taller than a mile, cruise ship designers have already packed nearly 7,000 people into a single vessel (*Symphony of the Seas*, built 2018), and people are dreaming about much larger floating cities. There are engineers who think that we will soon have wind turbines whose more than 200-meter-diameter blades will fold, like palm fronds, in hurricanes.

Depending on where you stand, you might see all of this either as an admirable quest for new horizons (a quintessential human striving) or irrational and wasteful overreach (a quintessential human hubris). ■

Illustration by John MacNeill

GIGANTISM IN THE AIR

Many flying behemoths have been tried, and most have failed. Of the three oversize planes shown in this illustration, the only one that has succeeded is the Antonov An-225, designed in the Soviet Union in the 1980s. This large cargo-lifter carries up to 250 tonnes of heavy machinery or construction parts on chartered flights to all continents.



Antonov An-225 Mriya
Wingspan: 88.4 meters
Length: 84 meters

Airbus A380-800
Wingspan: 64 meters
Length: 58.82 meters

Hughes H-4 Hercules ("Spruce Goose")
Wingspan: 97.82 meters
Length: 66.65 meters

Boeing 737-MAX7
Wingspan: 35.92 meters
Length: 35.56 meters

Meta Offers Nothing New to the Metaverse

Facebook's got a new name, but a tired business model

You may have heard that Facebook is owned by a company that is no longer called Facebook but, instead, Meta (officially Meta Platforms). CEO Mark Zuckerberg detailed the name change in a CGI-laden presentation that spanned an hour and 17 minutes. The metaverse, he says, is what's next for the Internet.

"The next platform and medium will be even more immersive, an embodied Internet where you're in the experience, not just looking at it," he said.

The announcement was not well received. Journalists, pundits, and politicians saw it as an attempt to deflect attention from Facebook's real, present problems by focusing on a better, imagined future. I share this view. As a consumer-technology journalist, however, I have a different problem with Facebook's vision of the metaverse: It's not new. Not even close.

Zuckerberg's demo was basically a virtual reality hangout. It depicted a small group of people playing a game of cards in VR before one of Zuckerberg's friends, taking the form of a robot, teleports him to a fantastic virtual forest. Zuckerberg is also shown admiring a VR art installation and using a video call to speak with friends in the "meataverse."

The show might have impressed those who are new to augmented and virtual reality. But the tech-savvy certainly know that everything shown by Facebook—sorry, Meta—is possible right now and has been for several years. It's not even that expensive.

An excellent VR setup with a Valve Index and fast PC costs about US $3,000. A passable setup with a Vive Pro 2 and a midrange PC is around $1,500. Or you can hop in with Meta's Oculus Quest 2 headset, which doesn't require a PC and starts at $299.

The experience doesn't fall far below Meta's demo. VRChat, a popular platform, has thousands of attractive 3D levels. The software can, if you opt for the more expensive VR setups, detect the movement of your limbs and face and animate your avatar to mimic your gestures and expressions. You can hang out with friends, play basic games, or explore virtual landscapes, as depicted in Meta's demonstration.

Everything shown by Facebook—sorry, Meta—is possible right now and has been for several years. It's not even that expensive.

VRChat is used by tens of thousands of people every day. A spike of users during New Years 2021 temporarily took down VRChat because the company's service provider thought it was experiencing a distributed denial of service attack.

Zuckerberg knows this. Facebook bought Oculus in 2014 and has released several iterations of Oculus hardware since. The company has its own virtual reality chat platform, Facebook Horizon, which more-or-less does what's shown in Meta's first demo but with less fidelity. VRChat is available on Oculus headsets along with competitors such as AltspaceVR and Rec Room. Still, the user base for VRChat and its ilk is tiny compared with Facebook's 2.91 billion active users.

Meta tried to set itself apart from the competition in a 10-minute segment toward the end of Zuckerberg's presentation. Michael Abrash, chief scientist of Meta's Reality Lab, showed prototype technology that will make avatars photorealistic, create lifelike interactive environments, and let users control input with subtle hand gestures.

All interesting stuff, and it will require a massive R&D effort. This, in part, is the reason for Facebook's change of name. The company plans to spend a lot of money on the metaverse. That could be hard to justify without signaling a shift away from Facebook.

Yet by focusing on what the metaverse can be in the future, Meta deflected from a question that cuts to the core of Zuckerberg's vision. If that VR vision is already accessible on hardware that costs as little as a midrange Android smartphone, why aren't consumers already eager to experience it?

That's the trillion-dollar question—and I don't think Meta has the answer. ■

Illustration by MCKIBILLO

So Much Moore

How we went from punch cards to teraflops

Whenever I hear someone rhapsodize about how much more computer power we have now compared with what was available in the 1960s during the Apollo era, I cringe. Those comparisons usually *grossly underestimate* the difference.

By 1961, a few universities around the world had bought IBM 7090 mainframes. The 7090 was the first line of all-transistor computers, and it cost US $20 million in today's money, or about 6,000 times as much as a top-of-the-line laptop today. Its early buyers typically deployed the computers as a shared resource for an entire campus. Very few users were fortunate enough to get as much as an hour of computer time per week.

The 7090 had a clock cycle of 2.18 microseconds, so the operating frequency was just under 500 kilohertz. But in those days, instructions were not pipelined, so most took more than one cycle to execute. Some integer arithmetic took up to 14 cycles, and a floating-point operation could hog up to 15. So the 7090 is generally estimated to have executed about 100,000 instructions per second. Most modern computer cores can operate at a sustained rate of 3 billion instructions per second, with much faster peak speeds. That is 30,000 times as fast, so a modern chip with four or eight cores is easily 100,000 times as fast.

A week of computing time on a modern laptop would take longer than the age of the universe on the 7090.

GAMMA-KEYSTONE/GETTY IMAGES

The IBM 7090 was the first line of transistorized computers, in the early 1960s. It was based on the 709 line, which used vacuum tubes.

Unlike the lucky person in 1961 who got an hour of computer time, you can run your laptop all the time, racking up more than 1,900 years of 7090 computer time every week. (Far be it from me to ask how many of those hours are spent on *Minecraft*.)

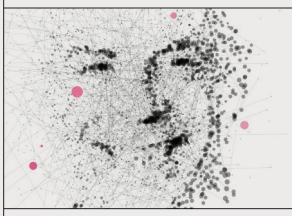
Continuing with this comparison, consider the number of instructions needed to train the popular natural-language AI model, GPT-3. Executing them on cloud servers took the equivalent of 355 years of laptop time, which translates to more than 36 million years on the 7090. You'd need a lot of coffee as you waited for that job to finish.

But, really, this comparison is unfair to today's computers. Your laptop probably has 16 gigabytes of main memory. The 7090 maxed out at 144 kilobytes. To run the same program would require an awful lot of shuffling of data into and out of the 7090—and it would have to be done using magnetic tapes. The best tape drives in those days had maximum data-transfer rates of 60 KB per second. Although 12 tape units could be attached to a single 7090 computer, that rate needed to be shared among them. But such sharing would require that a group of human operators swap tapes on the drives; to read (or write) 16 GB of data this way would take three days. So data transfer, too, was slower by a factor of about 100,000 compared with today's rate.

So now the 7090 looks to have run at about a quadrillionth (10^{-15}) the speed of your 2021 laptop. A week of computing time on a modern laptop would take longer than the age of the universe on the 7090.

But wait, there's more! Each core in your laptop has built-in SIMD (single instruction, multiple data) extensions that turbocharge floating-point arithmetic, used for vector operations. Not even a whiff of those on the 7090. And then there's the GPU, originally used for graphics speedup, but now used for the bulk of AI learning such as in training GPT-3. And the latest iPhone chip, the A15 Bionic, has not one, but five GPUs, as well as a bonus neural engine that runs 15 trillion arithmetic operations per second on top of all the other comparisons we have made.

The difference in just 60 years is mind boggling. But I wonder, are we using all that computation effectively to make as much difference as our forebears did after the leap from pencil and paper to the 7090? ■



Power Play

Kids grok AI, but not its pitfalls

The green light next to my computer's built-in webcam turned on. "Uh-oh," I thought to myself, realizing just then that the software I was trying out was recording me. My browser showed an image of my body with some dots placed over it, as the computer worked to map my posture. In using this software, I should have been down on the floor, stretched out, doing an isometric exercise known as the plank. But I wasn't, and the app eventually gave up trying to assess my performance, tut-tutting me for my poor form.

Making all of that happen in an app required the integration of many technologies: webcam live streaming, computer vision, and most significantly, a machine-learning model trained to discriminate a well-performed plank from my nonexistent effort. That entails quite a bit of work, most of it at the high end of what a software designer would typically be asked to deliver. But this amazing app had been written by a seventh grader.

For the last few decades, I've obsessively followed developments in interactive toys: the Furby and Lego Mindstorms, Sony's PlayStation and Bandai's Tamagotchi, all of it handed to kids without a second thought, and all of it shaping the way they think.

A child who chatted with a Furby 25 years ago has no trouble as an adult engaging with Alexa.

We often learn by playing—particularly when we're young. The objects we play with help us build an enduring model of the way things work. A child who chatted with a Furby 25 years ago has no trouble as an adult engaging with Alexa.

Today's kids have toys powered by artificial intelligence and are getting quite comfortable using it. Some of them are even able to apply AI to novel problems. I get to see this up close every year as a judge at an Australia-wide competition-cum-science-fair, where students prototype and present some incredibly creative IT projects.

A decade ago, a typical project might have involved an Arduino or a Raspberry Pi doing something clever like operating a scheduling system for a school playground. (Kids often solve problems they experience themselves.) This year saw an explosion of projects using Google's TensorFlow—such as that plank evaluator—and others using the still-in-beta application programming interface (API) for the awesomely powerful GPT-3 text-analysis engine from OpenAI.

Both have become accessible to secondary school students because Google and OpenAI recently released new APIs, making the sophisticated capabilities of these machine-learning systems easy to exploit. Kids dream up an application, then either adapt some existing code or just throw themselves into it and build something from scratch with the sort of obsessive focus adolescents find effortless.

Alongside Internet-of-Things and robotic projects, this year's crop of applications demonstrated that the next generation already understands the potential of AI and knows exactly how to use it to solve a problem. But they don't always grasp the pitfalls. That was particularly obvious in one of the apps I reviewed: Trained using a million Reddit comments, it reflected the worldview and experience of your average Redditor—a narrow enough base to inadvertently generate (and reinforce) unconscious biases.

These blind spots echo the broader challenge that AI poses. And they point to the growing importance of an education that includes both technical skills and a solid grounding in ethics. After all, with great power comes great responsibility. Youngsters have shown themselves adept at exercising these new AI powers; let's do what we can to make sure they're equally good at applying them responsibly. ■

Illustration by Adam Howling

TOP TECH 2022

NEURORIGHTS
DELIVERY DRONES
SMART VEHICLES
SUPERCOMPUTING
SPACEFLIGHT
MEMORY CHIPS
CRYTOCURRENCY

RENEWABLES
GEOENGINEERING
ROBOTICS
DISPLAYS
NUCLEAR FUSION
SEABED MINING
and more...

AT THE START OF EACH YEAR, *IEEE Spectrum* attempts to predict the future. It can be tricky, but we do our best, filling the January issue with a couple of dozen reports, short and long, about developments the editors *expect* to make news in the coming year. • This isn't hard to do when the project has been in the works for a long time and is progressing on schedule—the coming first flight of NASA's Space Launch System [p. 36], for example. For other stories, we must go farther out on a limb. A case in point: the description of a hardware wallet for Bitcoin that the company formerly known as Square (which recently changed its name to Block) is developing but won't officially comment on [p. 42]. One thing we can predict with confidence, though, is that *Spectrum* readers, familiar with the vicissitudes of technical development work, will understand if some of these projects don't, in fact, pan out. That's still okay. Engineering, like life, is as much about the journey as the destination. »»»

FIRST WIN FOR THE NEURORIGHTS CAMPAIGN

Chile plans to regulate all neurotech and ban the sale of brain data

BY ELIZA STRICKLAND

THE GOVERNment of Chile is taking a stand: Its citizens must be protected from technologies that are capable of mind control, mind reading, or any other nefarious interference with their brains. While such concerns used to be relegated to conspiracy-theory chat rooms and science fiction, now they're subject to debate by senators. Thanks to a constitutional amendment that was passed by the National Congress of Chile and signed by the president, the people of Chile are the first in the world to be granted a new kind of human rights—"neurorights"—which advocates say are made necessary by rapid advances in neurotechnology.

Neurotech includes brain implants that can read information from the brain, translating its electrical signals into, for example, movement commands for a prosthetic arm. Other implants change the brain by stimulating specific regions with electrical pulses. Such implanted stimulators are currently approved for only a few medical conditions, but Elon Musk has claimed that his neurotech company, Neuralink Corp., is developing implants that may one day be used by everyday people to enhance their cognitive abilities.

There are also a host of noninvasive technologies that can record from or stimulate the brain, some of which are approved for medical use. Other companies sell noninvasive neurotech directly to consumers for applications such as meditation, focus, and sleep; these devices need only meet the safety standards that govern consumer gadgets, not the far stricter regulations for medical devices regarding both safety and proof of clinical benefit.

Chile's congress is currently considering a bill that goes beyond the constitutional amendment's broad declaration of principles. The "neuroprotection" bill mandates that all neurotech devices be subjected to the same regulations as medical devices, even if they're intended for consumer wellness or entertainment. It also states that neural data will be considered equivalent to a human organ—which would prohibit the buying or selling of such data.

"Neuroscience is not just another field of knowledge," Senator Guido Girardi, the lead sponsor of the bill, tells *IEEE Spectrum* in an email. "It's similar to what atomic energy was in the 1950s. It may be used to develop a better society, but also to create weapons against humanity." Girardi says he hopes that Chile will be an example for the world, and that other nations and international agencies will adopt comparable regulation.

Indeed, 2022 may be the year that neurorights becomes a hot topic, bringing the young neurotech industry and the human rights community into uncomfortable conversations. Spain's new Digital Rights Charter includes a section on neurorights, and while it's a nonbinding framework, it may inspire new legislation. The United Nations' Secretary-General is also interested; his ambitious agenda, published last September, stated that it's time to "update our thinking on human rights," and included neurotechnology in a list of "frontier issues" to be considered. The debate is even coming to the big screen: Werner Herzog, the German film director, is expected to premiere a film about neurorights, *Theater of Thought*, sometime in 2022.

While some neuroscientists and bioethicists support the global campaign, others say Chile is setting a problematic example for the world and that its rushed regulations haven't been properly thought through. Concepts such as "brain data" need to be clarified, critics say, because a broad definition could include behavioral data that reflects what's going on in a person's mind, which many companies already collect.

The debate can quickly get philosophical: Do people have fixed mental identities throughout their lives? Does anyone have free will? And what do the squiggly patterns of electrical activity that can be recorded from a person's brain reveal about them? Rafael Yuste, cofounder of the NeuroRights Foundation, in New York City, believes

Photo-illustration by Edmon de Haro

that the technology is forcing such questions upon us. "This is something that affects the essence of what it means to be human," he says.

THE NEURORIGHTS Foundation can claim much of the credit for the developments in Chile, Spain, and the U.N. Yuste, a professor of biology at Columbia University who studies neural circuitry, has been promoting the idea of neurorights for nearly a decade now. He first raised the issue through his involvement with the U.S. Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative, a US $100 million research effort announced by President Barack Obama in 2013. Yuste next convened a group of neuroscientists, clinicians, ethicists, and engineers to come up with ethical priorities for neurotechnology, which they published in a 2017 *Nature* paper. With his colleagues at the foundation, he has worked closely with the policymakers who have made the first moves on neurorights. Yuste says he's been driven by the implications of his own scientific research: "We're decoding perceptions and memory in mice," he says, "so it's just a matter of time until this happens in humans."

The foundation has delineated five basic neurorights, starting with the right to mental privacy. Medical and consumer neurotech devices collect the most intimate kind of data about us, Yuste says; even if current technologies can decode only a small fraction of it, the data may become increasingly revealing as the technology improves. The next two rights protect against the misuse of neurotech that stimulates the brain and alters its activity: People should have the right to maintain their personal identity and to exercise free will. The final two rights are broader guidelines for society: People should have equal access to mental-augmentation technologies, and the technology should be free from algorithmic bias that makes the technology work better for certain groups.

Legal scholars working with the NeuroRights Foundation say the right to mental privacy is under the most imminent threat. Staff attorney Stephanie Herrmann of Perseus Strategies, a law firm specializing in international human rights, points to a few articles in recent years that have raised alarms about new kinds of neuro-surveillance. One report from the *South China Morning Post* highlighted a manufacturing company that was supposedly using brain-scanning headsets to monitor its workers' emotional and cognitive states, while another article from that publication showed school-children wearing headbands that indicated whether they were paying attention to their lesson.

"All of these technologies are so far ahead of where we are in our thinking about them," Herrmann tells *IEEE Spectrum*. In an article published in the journal *Horizons,* Herrmann, Yuste, and Perseus Strategies director Jared Genser argue that the U.N. should set global standards for neurorights, paving the way for nations to pass their own laws. "Regulations are very much part of the future," Herrmann says, "but establishing an international framework for thinking about how to regulate is a good start."

Herrmann also notes that human-rights laws often protect individuals against harmful actions by the state, and says that it's easy to envision misuse of neurotech by governments. Beyond the potential for surveillance, she notes that a 2020 U.N. report on psychological torture contained a discussion of emerging technologies that

KERNEL

The Flow headset from Kernel uses near-infrared light to measure blood flow in the brain. Kernel is currently selling the device to researchers, but the company is also developing a consumer model.

could be used to inflict new kinds of pain and suffering, naming neurotechnology as one to watch. Torturers could alter a victim's subjective experience of pain, Herrmann suggests, or interfere with their sense of autonomy.

Yuste worries more about the private companies that are now pouring money into neurotech R&D, particularly those that sell directly to customers and are regulated only as consumer electronics. He notes that many neurotech companies own the data that they extract from users' brains. "The company is free to decode the data, to sell it, to do whatever they want with it," he says. Do you feel uncomfortable when you consider how much Facebook knows about you based on your online activity? Now imagine if the company had your brain data as well.

NOW LET'S TALK about hype. Critics say that news reports like those in the *South China Morning Post* vastly overstate the current technology's capabilities, potentially causing hysteria. "People are being swept up in the hype around how scary these things are," says Karen Rommelfanger, founder of Emory University's neuroethics program and the new nonprofit Institute of Neuroethics.

External headsets, like those supposedly worn by workers and students in China, provide fairly crude types of data decoding or stimulation. The most powerful and high-fidelity neurotech devices are those implanted in the brain, but even implants are far from being able to read someone's thoughts or force them to act against their will. For example, researchers at the University of California, San Francisco, have done pioneering work with implants that can decode words from the brains of stroke patients who have lost the ability to speak, but their latest study used a vocabulary set of only 50 words. Facebook (now Meta) had helped fund that research as part of its effort to build a brain-computer interface for consumers that would translate "intended speech" into text, but in July the company announced that it was abandoning that effort.

Rommelfanger is strongly in favor of national and international discussions of neuroethics, but she says the Chilean efforts on neurorights were rushed and didn't incorporate enough local input. "If you dig into the local literature, you'll see that philosophers, clinicians, lawyers, and even digital-rights groups have all offered critiques of the laws." She says that some Chilean legal and medical experts have raised concerns about turning broad principles into clear rules. For example, she asks, "What does it mean to have psychic continuity?" Some could argue that giving a depressed person antidepressant medication changes who they are—hence, she says, the concerns from medical groups that the neuro-protection law could hamper their ability to treat patients.

Rommelfanger thinks that the approach taken by the Chilean bill for neuroprotection is too heavy-handed; by regulating all neurotech as medical devices, she worries that the country will stifle innovation and prevent startups from bringing forth new devices that will help people. And Chile's actions are getting international attention: "I'm afraid that other governments are going to move too fast, like what Chile has done, which will foreclose their opportunity to develop neurotech," she says. It might be wiser, she says, to start with a review of existing human rights and

CONTINUED ON PAGE 58

6-Gigahertz Wi-Fi Goes Mainstream

WI-FI IS GETTING a boost with 1,200 megahertz of new spectrum in the 6-gigahertz band, adding a third spectrum band to the more familiar 2.4 GHz and 5 GHz. The new band is called Wi-Fi 6E because it extends Wi-Fi's capabilities into the 6-GHz band. As a rule, higher radio frequencies have higher data capacity, but a shorter range. With its higher frequencies, 6-GHz Wi-Fi is expected to find use in heavy traffic environments like offices and public hotspots. The Wi-Fi Alliance introduced a Wi-Fi 6E certification program in January 2021, and the first trickle of 6E routers appeared by the end of the year. In 2022, expect to see a bonanza of Wi-Fi 6E–enabled smartphones. *—Michael Koziol*

Illustration by MCKIBILLO

FLYING PALLETS WITHOUT PILOTS

A drone startup will test a radical new vision of long-range cargo transport in Europe • **BY PHILIP E. ROSS**

DELIVERING things by drone began as a stunt in 2012, when a model airplane dropped a burrito by parachute to a hungry customer waiting below. The concept then graduated, first to a proof-of-principle venture in Iceland using multicopters, then to a well-funded Amazon project in the United Kingdom. But these and similar attempts to solve the last-mile problem—the mile leading to the customer—have largely been disappointing. Amazon recently scaled back its drone-based delivery project in the U.K.

In 2022, Dronamics, a company based in London and Sofia, Bulgaria, will test-fly a drone in Europe that will carry far more than a mere burrito and over far longer distances. It addresses the less sexy but equally important middle-distance problem—the route that connects factories to warehouses. The point is to take a slice of business that's now handled by regular air freight and by trucks—above all, the quick delivery of critical parts. If this service had been available a year or two ago, it might not have prevented the logistics logjam that now plagues the world, but it would have cleared away some of the more problematic bottlenecks.

Dronamics will run trials with its partners, including DHL and Hellmann Worldwide Logistics, in the hope of eventually fielding thousands of drones, each carrying as much as 350 kilograms of cargo up to 2,500 kilometers. The European Union has facilitated this sort of experimentation by instituting a single certification policy for drone aircraft. Once its aircraft are certified, Dronamics must get a route approved through one of the E.U.'s member countries; that done, it should be fairly easy to get other member countries to agree as well.

In October, Dronamics announced that it would use Malta as its base, with a view to connecting first to Italy and later to other Mediterranean countries.

One thing Dronamics doesn't do is full-scale autonomy: Its planes do not detect and avoid obstacles. Instead, each flight is programmed in advance, in a purely deterministic way. Flights often take place in controlled airspace and always between drone ports that the company controls. Someone on the ground monitors the flight from afar, and if something unexpected arises, that person can redirect the plane.

"We operate like a proper airline, but we can intervene," says Svilen Rangelov, the cofounder and CEO of Dronamics. "We're looking for underserved airports, using time slots where there is no passenger traffic. In the United States there are 17,000 airports, but only about 400 are commercially used. The rest don't have regular service at all."

UNLIKE THE EARLY multicopter burrito drones, or even Amazon's prototypes, these machines fly on fixed wings and are powered by internal combustion engines, the better to carry big loads long distances and to operate at off-the-grid airfields. "Anything less than 200 miles [about 320 kilometers] is not appropriate because, given the time to get to the airport, fly, and then pick up, you may as well truck it," Rangelov says.

A Black Swan drone, from Dronamics, stands at the ready.

DRONAMICS

The company's drone is called Black Swan, a phrase often used to describe important but unpredictable events. "That was precisely the reasoning" behind the name, Rangelov says, explaining what makes this drone so unique and rare. "We knew [the drone] had to be cheaper to produce and to operate than any existing models."

Because this vehicle is intended to transport cargo with no people on board, Dronamics could design the interior to fit cargo pallets. "It's exactly the right cargo size for this business," Rangelov says. "It likely will not be carrying one pallet of the same things but multiple packages for many customers." And Dronamics claims it can carry cargo for half of what today's air freighters charge.

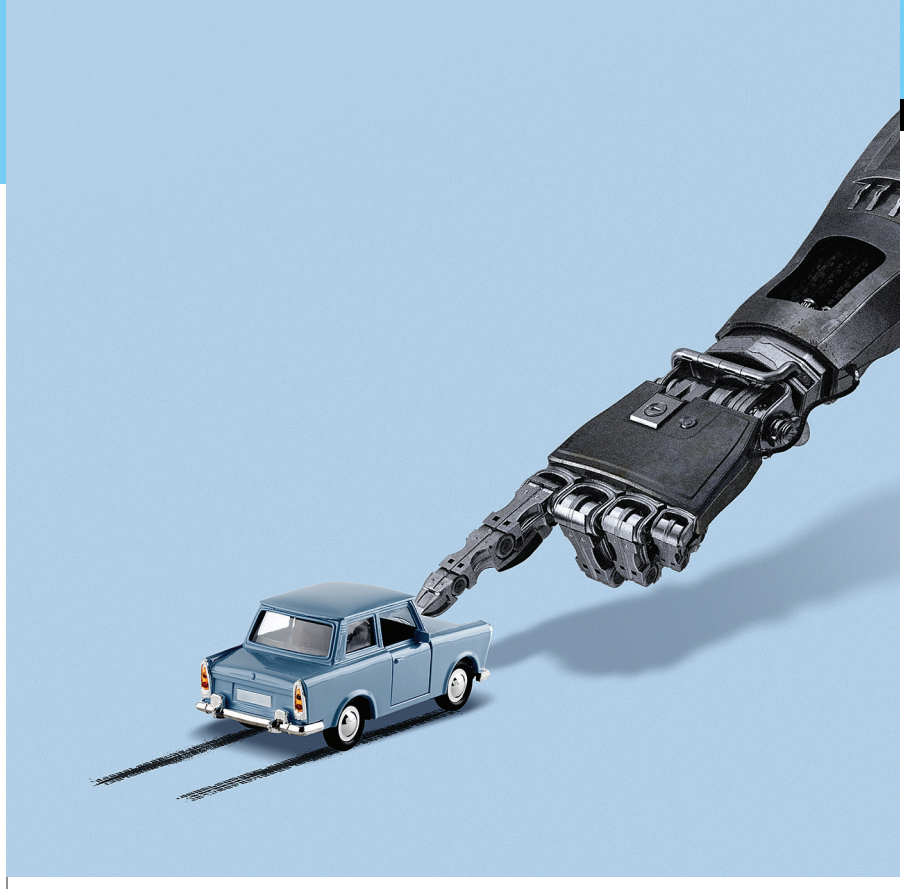
Hellmann Worldwide Logistics sees a lot of potential for using Dronamics in Africa and other places with limited infrastructure. For now, though, the company is focused on the dense population, manageable distances, and supportive governmental institutions of Europe.

"Especially between north and south Europe—from Germany and Hungary, where there's a lot of automotive business," says Jan Kleine-Lasthues, Hellmann's chief operating officer for air freight. There are also supply lines going into Italy that service the cruise ships on the Mediterranean Sea, he says, and fresh fish would be ideal cargo. Indeed, Dronamics is working on a temperature-controlled container.

What effect would massive fleets of such drones have had on today's supply-chain problems? "It could help," he says. "If the container isn't arriving with production material, we could use drones to keep production alive. But it's not replacing the big flow—it's just a more flexible, more agile mode of transport."

Before cargo drones darken the skies, though, Hellmann wants to see how the rollout goes.

"First of all, we want to try it," Kleine-Lasthues says. "One use case is replacing commercial air freight—for example, Frankfurt to Barcelona by drone; also, there's a use case replacing vans. If it is working, I think it can be quickly ramped up. The question is how fast can Dronamics add capacity to the market." ■



BRAKES THAT SLAM THEMSELVES

Automatic emergency braking will become standard in Europe

BY PHILIP E. ROSS

In 2022, cars in many countries must start carrying automatic emergency braking. The technology has been around for years, but requiring it marks a major safety milestone for active safety. That's the sort that prevents a crash instead of protecting you from its effects.

The European Transport Safety Council, a not-for-profit advocacy group in Brussels, estimates that automatic braking can reduce traffic death rates by as much as 20 percent. That's about 4,000 lives saved each year.

The system—which uses cameras or radar to tell when danger's up ahead and, if need be, hits the brakes—will be required in May in the European Union. In the United States all models that are new in 2022 come with it, although compliance is voluntary, pending formal rulemaking. Similar rules are also going into effect this year in dozens of other countries.

The EU's regulations, conceived in 2019, seem to go the furthest, requiring as they do a number of other advanced driver assistance systems—notably emergency lane-keeping assist, drowsiness and distraction recognition, and intelligent speed assistance. That last one works by holding the car within the local speed limit not by braking but by limiting the power the engine sends to the wheels.

The rules require that the driver retain the power to override the systems, which makes for less intrusive nannying. Some people, however, kind of like being nannied. A case in point is intelligent speed assistance, which Ford has offered in Europe on the S-Max since 2015 and on the more affordable Focus since 2017, well before the EU had even decided to make it mandatory.

"In scientific trials, people were a bit resistant to [intelligent speed assistance], but once they got used to it they actually appreciated it," says Dudley Curtis, a spokesman for the European advocacy group. "Ford marketed it by saying this was a way of never getting a speeding ticket again."

Mandates aren't the only way. Back in the 1970s, when antilock braking—the original active safety feature—started to become common, customers rushed to buy it as an option because they loved the way it stopped the car on slick pavement. Manufacturers made it standard before government agencies got around to telling them to. Formal requirements came long afterwards—in Europe in 2004 and in the United States in 2012.

Now the world is more tightly regulated—witness rubberized playgrounds—and the automotive world is tighter still. That's because it's moving toward the dream of self-driving vehicles, which demands

Photo-illustration by Edmon de Haro

EUROPE NOW REQUIRES EMERGENCY BRAKING TO PROTECT ONLY AGAINST FORWARD COLLISIONS; IT HAS BROADER GOALS FOR 2024.

universal standards. Baby steps that sneak toward that goal also demand tough standards.

The baby step that preceded emergency braking is known as forward-collision avoidance. When sensors see the car closing fast on an obstacle, the system flashes a light, buzzes an alarm, or even shakes the steering wheel, to rouse the driver to action; at the same time, it precharges the braking assist system to respond quickly when the driver does act. An emergency-braking system still does all that—if only to avoid startling the driver—but if it can't coax the driver into braking, it will do so itself.

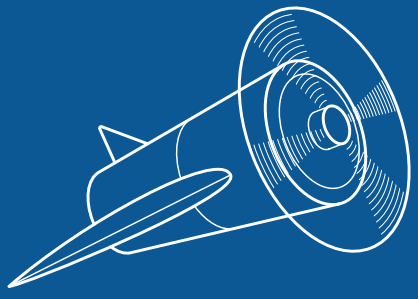
Deferring to the person behind the wheel checks a lot of boxes—human pride, legal niggling, and the engineer's fear of false positives. These do happen: Some experimental robocars have been known to stop dead in their tracks after mistaking a shadow for something more substantial. Today's systems still can't flawlessly identify objects smaller than a vehicle, such as a pedestrian or squirrel, or look at everything that may be happening all around the car.

That's why the current European regulations require emergency braking to protect only against forward collisions, and only against collisions with big vehicles, not cyclists or pedestrians. Broader goals are on the EU's safety agenda for 2024. (Note that this year's requirements apply in full force only to completely new models; existing models will have until 2024 to comply.)

When *IEEE Spectrum* asked the U.S. National Highway Traffic Safety Administration why automatic braking is still only voluntary, the agency replied in an email that in 2022 it would issue a notice for comments on proposals that would require a braking standard that applies to both vehicles and pedestrians. That puts U.S. regulators about where the Europeans stood three years ago.

"America has done very little," says Curtis. "But there are plenty of places in Europe that are problematic. Every year we do a report on mortality rates; the safest are still Sweden, the Netherlands—and I was going to say the United Kingdom, but my country has left the EU. At the other extreme are Bulgaria and Romania—Spain was doing poorly, but in a very few years it has come up to near the top of the list."

All to say, drivers the world over can learn to drive more safely, and in 2022 a lot more of them will be getting a little technological help with that. ■

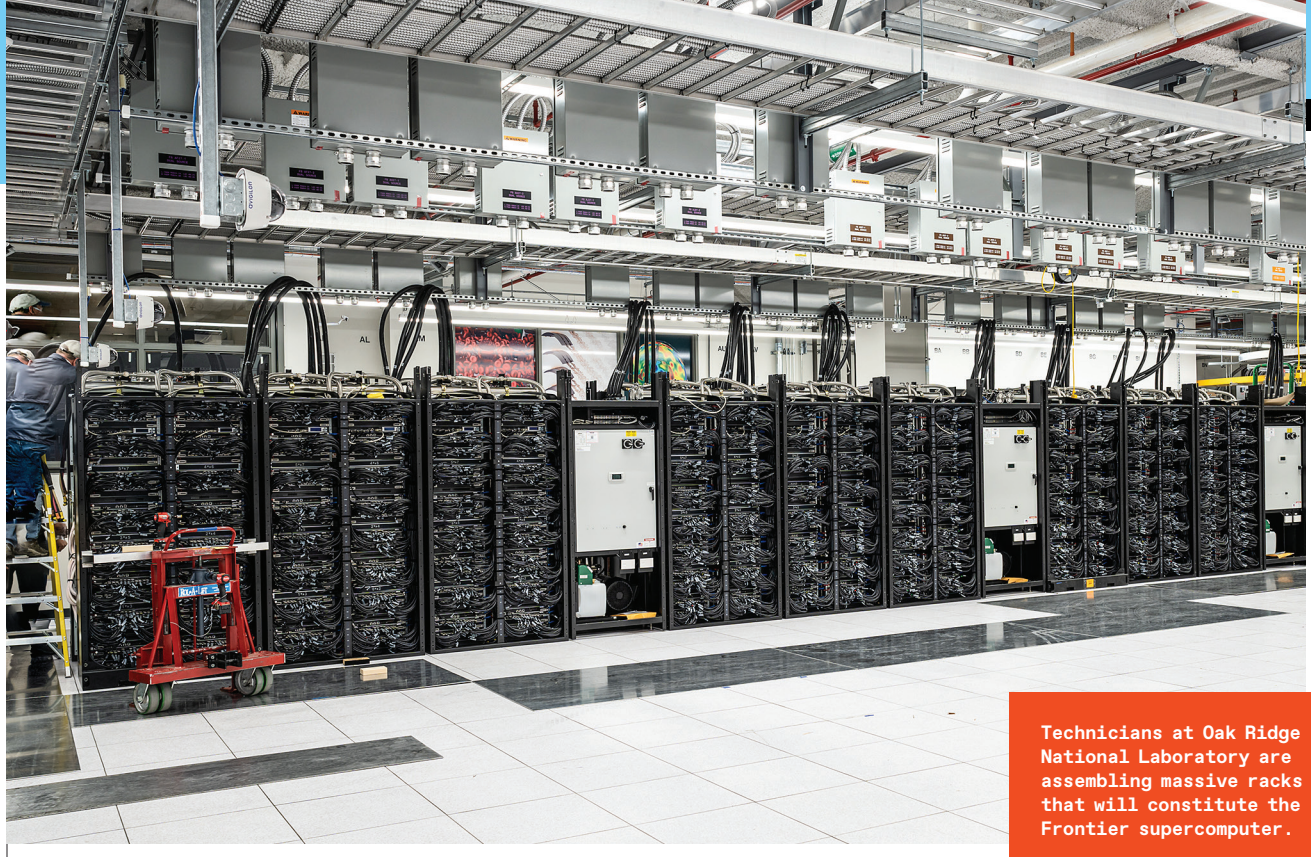


The Great Electric Plane Race

FOR THE FIRST TIME in almost a century, the U.S.-based National Aeronautic Association (NAA) will host a cross-country aircraft race. Unlike the national air races of the 1920s, however, the Pulitzer Electric Aircraft Race, scheduled for 19 May, will include only electric-propulsion aircraft. Both fixed-wing craft and helicopters are eligible. The competition will be limited to 25 contestants, and each aircraft must have an onboard pilot. The course will start in Omaha and end four days later in Manteo, N.C., near the site of the Wright brothers' first flight. The NAA has stated that the goal of the cross-country, multiday race is to force competitors to confront logistical problems that still plague electric aircraft, like range, battery charging, reliability, and speed.

—Michael Koziol

Illustration by MCKIBILLO



Technicians at Oak Ridge National Laboratory are assembling massive racks that will constitute the Frontier supercomputer.

THE EXASCALE ERA IS UPON US

The Frontier supercomputer may be the first to reach 1,000,000,000,000,000,000 operations per second

BY DAVID SCHNEIDER

In 2018, a new supercomputer called Summit was installed at Oak Ridge National Laboratory, in Tennessee. Its theoretical peak capacity was nearly 200 petaflops—that's 200 *thousand trillion* floating-point operations per second. At the time, it was the most powerful supercomputer in the world, beating out the previous record holder, China's Sunway TaihuLight, by a comfortable margin, according to the well-known Top500 ranking of supercomputers. (Summit is currently No. 2, a Japanese supercomputer called Fugaku having since overtaken it.)

In just four short years, though, demand for supercomputing services at Oak Ridge has outstripped what even this colossal machine can provide. "Summit is four to five times oversubscribed," says Justin Whitt, who directs ORNL's Leadership Computing Facility. "That limits the number of research projects that can use it."

The obvious remedy is to get a faster supercomputer. And that's exactly what Oak Ridge is doing. The new supercomputer being assembled there is called Frontier. When complete, its peak theoretical capacity will exceed 1.5 exaflops.

The remarkable thing about Frontier is not that it will be more than seven times as powerful as Summit, stunning as that figure is. The remarkable thing is that it will use only twice the power. That's still a lot of power—Frontier is expected to draw 29 megawatts, enough to power a town the size of Cupertino, Calif. But it's a manageable amount, both in terms of what the grid there can supply and what the electricity bill will be.

"The efficiency comes from putting more computer hardware in smaller and smaller spaces," says Whitt. "Each of these [computer] cabinets weighs as much as a full-sized pickup." That's because they are stuffed with what ORNL's spec sheet describes as "high density compute blades powered by HPC- and AI-optimized AMD EPYC processors and Radeon Instinct GPU accelerators purpose-built for the needs of exascale computing."

Building a supercomputer of this capacity is hard enough. But doing so during a pandemic has been especially challenging. "Supply-chain issues were

OAK RIDGE NATIONAL LABORATORY

broad," says Whitt, including shortages of many things that aren't special to building a high-performance supercomputer. "It could just be sheet metal or screws."

Supply issues are indeed the reason Frontier will become operational in 2022 ahead of another planned supercomputer, Aurora, which will be installed at Argonne National Laboratory, in Illinois. Aurora was to come first, but its construction has been delayed, because Intel is having difficulty supplying the processors and GPUs needed for this machine.

AT THE TIME of this writing, technicians at Oak Ridge were assembling and testing parts of Frontier in hopes that the giant machine will come together before the end of 2021 and with the intention of making it fully operational and available for users in 2022. Will we then be able to call it the world's first exascale supercomputer?

That depends on your definition. "[Japan's Fugaku supercomputer] actually achieved 2 exaflops with a different benchmark," says Jack Dongarra of the University of Tennessee, one of the specialists behind the Top500 list. Those rankings, he explains, are based on a benchmark that involves 64-bit floating-point calculations, the kind used to solve three-dimensional partial differential equations as required for many physical simulations. "That's the bottom line of what supercomputers are being used for," says Dongarra. But he also points out that supercomputers are increasingly used to train deep neural networks, where 16-bit precision can suffice.

And then there's Folding@Home, a distributed-computing project intended to simulate protein folding. "I would call that a specialized computer," says Dongarra, one that can do its job because the calculations involved are "embarrassingly parallel." That is, separate computers can perform the required calculations independently—or at least largely so, with what little communication between them is needed being conveyed over the Internet. In March of 2020, the Folding@Home project proudly announced on Twitter, "We've crossed the exaflop barrier!"

But if you stick with the usual benchmark, the one used for the Top500 ranking, no supercomputer yet qualifies as an exascale machine. Frontier may be the first. Or well, it's on track to be the first *known* exascale supercomputer, says Dongarra. He explains that before the June 2021 Top500 ranking came out, a rumor emerged that China has at least one, if not two, supercomputers already running at exascale.

Why would Chinese engineers construct such a machine without telling anyone about it? At the time, Dongarra says, he thought that maybe they were waiting for the 100-year anniversary of the founding of the Chinese communist party. But that date came and went in July. He now speculates that Chinese officials may be worried that making its existence public would exacerbate geopolitical rivalries and cause the United States to restrict the export of certain technologies to China.

Perhaps that explains it. But it's going to be increasingly difficult for Chinese researchers not to let this cat, if it truly exists, out of the bag. For the moment, anyway, with only rumors to go on, this exascale rival to Frontier is a Schrödinger's cat—both here and not here at the same time. ■

Seoul Joins the Metaverse

AFTER FACEBOOK (now Meta) announced it was hell-bent on making the metaverse real, a host of other tech companies followed suit. Definitions differ, but the basic idea of the metaverse involves merging virtual reality and augmented reality with actual reality. Also jumping on the metaverse bandwagon is the government of the South Korean capital, Seoul, which plans to develop a "metaverse platform" by the end of 2022. To build this first public metaverse, Seoul will invest 3.9 billion won (US $3.3 million). The platform will offer public services and cultural events, beginning with the Metaverse 120 Center, a virtual-reality portal for citizens to address concerns that previously required a trip to city hall. Other planned projects include virtual exhibition halls for school courses and a digital representation of Deoksu Palace. The city expects the project to be complete by 2026.

—Michael Koziol

Illustration by MCKIBILLO

NASA'S SPACE LAUNCH SYSTEM WILL LIFT OFF

But with rival rockets readying for flight, the ultimate value of SLS is murky

BY JEFF FOUST

INSIDE THE VEHICLE Assembly Building (VAB) at NASA's Kennedy Space Center in Florida—a cavernous structure built in the 1960s for constructing the Apollo program's Saturn V rockets and, later, for preparing the space shuttle—the agency's next big rocket is taking shape.

Tom Whitmeyer, NASA's deputy associate administrator for exploration system development, recalled seeing the completed Space Launch System (SLS) vehicle there in October, after the last component, the Orion spacecraft, was installed on top. To fully view the 98-meter-tall vehicle, he had to back off to the opposite side of the building.

"It's taller than the Statue of Liberty," he said at an October 2021 briefing about the rocket's impending launch. "And I like to think of it as the Statue of Liberty, because it's [a] very engineering-complicated piece of equipment, and it's very inclusive. It represents everybody."

Perhaps so. But it's also symbolic of NASA's way of developing rockets, which is often characterized by cost overruns and delays. As this giant vehicle nears its first launch later this year, it runs the risk of being overtaken by commercial rockets that have benefited from new technologies and new approaches to development.

NASA'S NEWEST ROCKET didn't originate in the VAB, of course—it began life on Capitol Hill. In 2010, the Obama administration announced its intent to cancel NASA's Constellation program for returning people to the moon, citing rising costs and delays. Some in Congress pushed back, worried about the effect on the space industry of canceling Constellation at the same time NASA was retiring its space shuttles.

The White House and Congress reached a compromise in a 2010 NASA authorization bill. It directed the agency to develop a new rocket, the Space Launch System, using technologies and contracts already in place for the shuttle program. The goal was to have a rocket capable of placing at least 70 tonnes into orbit by the end of 2016.

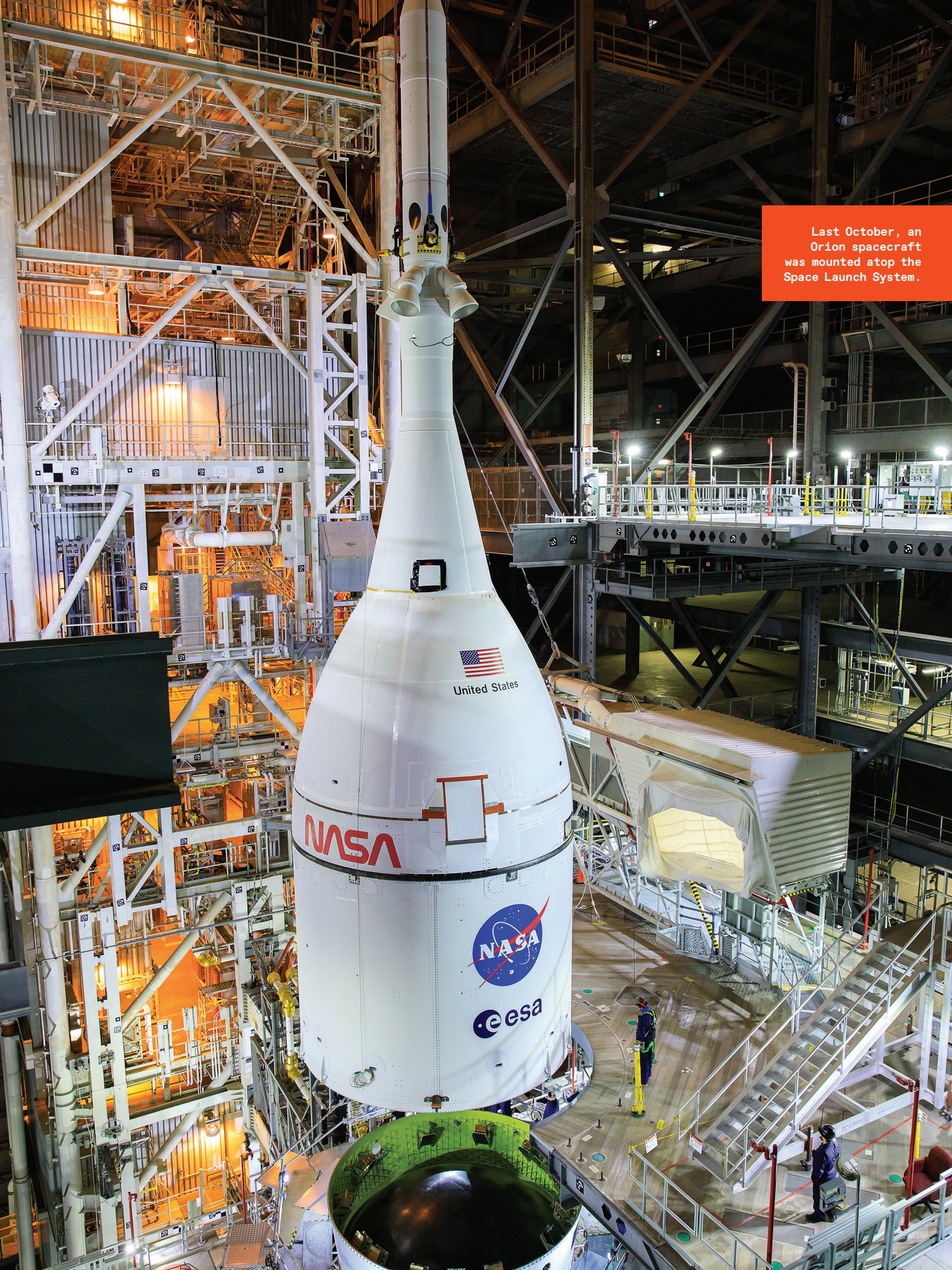
To achieve that, NASA extensively repurposed shuttle hardware. The core stage of SLS is a modified version of the external tank from the shuttle, with four RS-25 engines developed for the shuttle mounted on its base. Attached to the sides of the core stage are two solid-rocket boosters, similar to those used on the shuttle but with five segments of solid fuel instead of four.

Mounted on top of the core stage is what's called the Interim Cryogenic Propulsion Stage, which is based on the upper stage for the Delta IV rocket and is powered by one RL10 engine, a design that has been used for decades. This stage will propel the Orion capsule to the moon or beyond after it has attained orbit. As the name suggests, this stage is a temporary one: NASA is developing a more powerful Exploration Upper Stage, with four RL10 engines. But it won't be ready until the mid-2020s.

Even though SLS uses many existing components and was not designed for reusability, combining those components to create a new rocket proved more difficult than expected. The core stage, in particular, turned out to be surprisingly complex, as NASA struggled with the challenge of incorporating four engines. Once the first core stage was complete, it spent more than a year on a test stand at NASA's Stennis Space Center in Mississippi, including two static-fire tests of its engines, before going to the Kennedy Space Center for launch preparations.

Those difficulties pushed back the first SLS launch by years, although not all the problems were within NASA's control. Hurricanes damaged the Stennis test stand as well as the New Orleans facility where the core stage is built. The pandemic also slowed the work, before and after all the components arrived at the VAB for assembly. "In Florida in August and September [2021], it hit our area very hard," said Mike Bolger, manager of the exploration ground

FRANK MICHAUX/NASA



Last October, an Orion spacecraft was mounted atop the Space Launch System.

systems program at NASA, describing the most recent wave of the pandemic at the October briefing.

Now, after years of delays, the first launch of the SLS is finally getting close. "Completing stacking [of the SLS] is a really important milestone. It shows that we're in the home stretch," said Mike Sarafin, NASA's manager for the first SLS mission, called Artemis 1, at the same briefing.

After a series of tests inside the VAB, the completed vehicle will roll out to Launch Complex 39B. NASA will then conduct a practice countdown called a wet dress rehearsal—"wet" because the core stage will be loaded with liquid-hydrogen and liquid-oxygen propellants.

Controllers will go through the same steps as in an actual countdown, stopping just before the point where the RS-25 engines would normally ignite. "For us, on the ground, it's a great chance to get the team and the ground systems wrung out and ready for launch," Bolger said of the wet dress rehearsal.

After that test, the SLS will roll back to the VAB for final checks before returning to the pad for the actual launch. The earliest possible launch for Artemis 1 is 12 February 2022, but at the time of this writing, NASA officials said it was too soon to commit to a specific launch date.

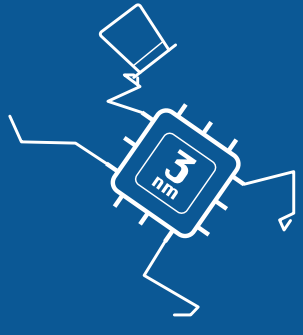
"We won't really be in a position to set a specific launch date until we have a successful wet dress [rehearsal]," Whitmeyer said. "We really want to see the results of that test, see how we're doing, see if there's anything we need to do, before we get ready to launch."

To send the uncrewed Orion spacecraft to the moon on its desired trajectory, SLS will have to launch in one of a series of two-week launch windows, dictated by a variety of constraints. The first launch window runs through 27 February. A second opens on 12 March and runs through 27 March, followed by a third from 8 to 23 April. Sarafin said there's a "rolling analysis cycle" to calculate specific launch opportunities each day.

A complicating factor here is the supply of propellants available. The core stage's tanks store 2 million liters of liquid hydrogen and almost three-quarters of a million liters of liquid oxygen, putting a strain on the liquid hydrogen available at the Kennedy Space Center.

"This rocket is so big, and we need so much liquid hydrogen, that our current infrastructure at the Kennedy Space Center just does not support an every-day launch attempt," Sarafin said. If a launch attempt is postponed after the core stage is fueled, Bolger explained, NASA would have to wait days to try again. That's because a significant fraction of liquid hydrogen is lost to boil-off during each launch attempt, requiring storage tanks to be refilled before the next attempt. "We are currently upgrading our infrastructure," he said, but improvements like larger liquid hydrogen storage tanks won't be ready until the second SLS mission in 2023. There's no pressure to launch on a specific day, Sarafin said. "We're going to fly when the hardware's ready to fly."

SLS IS NOT the only game in town when it comes to large rockets. In a factory located just outside the gates of the Kennedy Space Center, Blue Origin, the spaceflight company founded by Amazon's Jeff Bezos, is working on its New Glenn rocket. While not as powerful as SLS, its ability to place up to 45 tonnes into

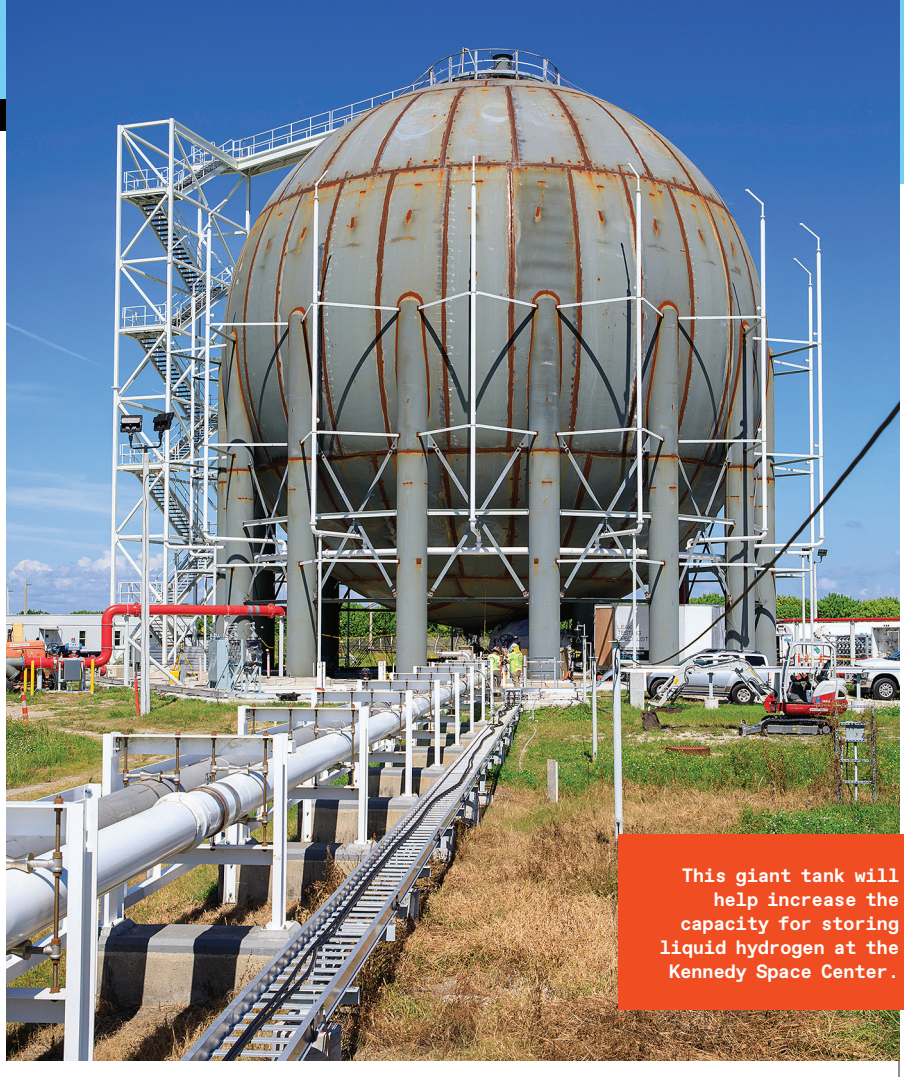


3-Nanometer Chips Arrive

TAIWAN SEMICONDUCTOR Manufacturing Co. (TSMC) plans to begin producing 3-nanometer semiconductor chips in the second half of 2022. Right now, 5-nm chips are the standard. TSMC will make its 3-nm chips using a tried-and-true semiconductor structure called the FinFET (short for "fin field-effect transistor"). Meanwhile, Samsung and Intel are moving to a different technique for 3 nm called nanosheet. (TSMC is eventually planning to abandon FinFETs.) At one point, TSMC's sole 3-nm chip customer for 2022 was Apple, for the latter's iPhone 14, but supply-chain issues have made it less certain that TSMC will be able to produce enough chips—which promise more design flexibility—to fulfill even that order.

—Michael Koziol

Illustration by MCKIBILLO



This giant tank will help increase the capacity for storing liquid hydrogen at the Kennedy Space Center.

GLENN BENSON/NASA

orbit outclasses most other rockets in service today. Moreover, unlike SLS, the rocket's first stage is reusable, designed to land on a ship.

New Glenn and SLS do have something in common: development delays. Blue Origin once projected the first launch of the rocket to be in 2020. By early 2021, though, that launch date had slipped to no earlier than the fourth quarter of 2022.

A key factor in that schedule is the development of Blue Origin's BE-4 engine, seven of which will power New Glenn's first stage. Testing that engine has taken longer than expected, affecting not only New Glenn but also United Launch Alliance's new Vulcan Centaur rocket, which uses two BE-4 engines in its first stage. Vulcan's first flight has slipped to early 2022, and New Glenn could see more delays as well.

Meanwhile, halfway across the country, at the southern tip of Texas, SpaceX is moving ahead at full speed with its next-generation launch system, Starship. For two years, the company has been busy building, testing, flying—and often crashing—prototypes of the vehicle, culminating in a successful flight in May 2021 when the vehicle lifted off, flew to an altitude of 10 kilometers, and landed.

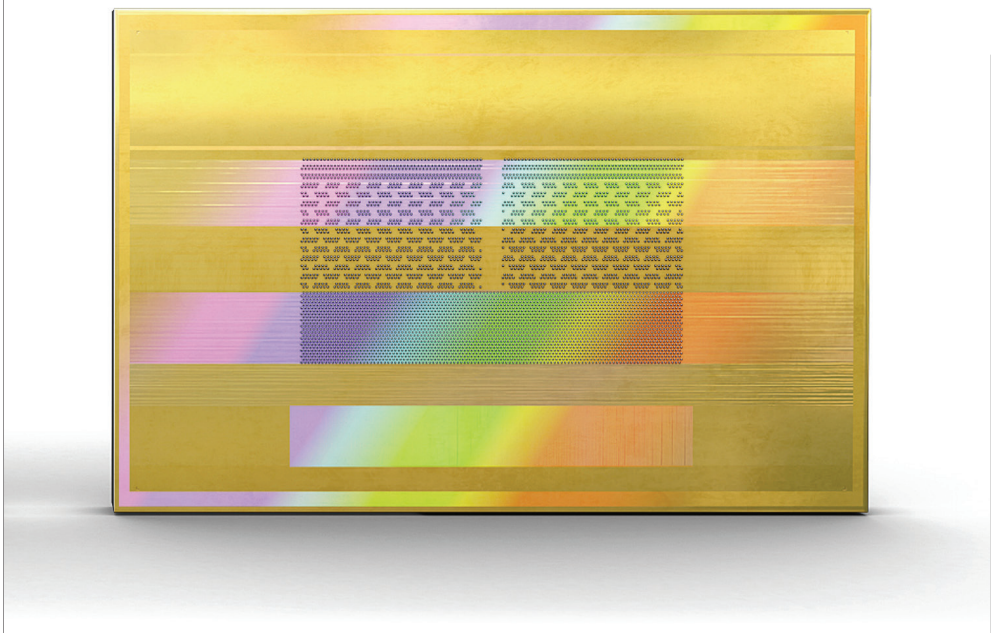
SpaceX is now preparing for orbital test flights, installing the Starship vehicle on top of a giant booster called, aptly, Super Heavy. A first test flight will see Super Heavy lift off from the Boca Chica, Texas, test site and place Starship in orbit. Starship will make less than one lap around the planet, though, reentering the atmosphere and splashing down in the Pacific about 100 kilometers from the Hawaiian island of Kauai.

When that launch will take place remains uncertain—despite some optimistic announcements. "If all goes well, Starship will be ready for its first orbital launch attempt next month, pending regulatory approval," SpaceX CEO Elon Musk tweeted on 22 October 2021. But Musk surely must have known at the time that regulatory approval would take much longer.

SpaceX needs a launch license from the U.S. Federal Aviation Administration to perform that orbital launch, and that license, in turn, depends on an ongoing environmental review of Starship launches from Boca Chica. The FAA hasn't set a schedule for completing that review. But the draft version was open for public comments through the beginning of November, and it's likely to take the FAA months to review those comments and incorporate them into the final version of the report. That suggests that the initial orbital flight of Starship atop Super Heavy will also take place sometime in early 2022.

Starship could put NASA in a bind. The agency is funding a version of Starship to serve as a lunar lander for the Artemis program, transporting astronauts to and from the surface of the moon as soon as 2025. So NASA clearly wants Starship development to proceed apace. But a successful Starship launch vehicle, fully reusable and able to place 100 tonnes into orbit, could also make the SLS obsolete.

Of course, on the eve of the first SLS launch, NASA isn't going to give up on the vehicle it's worked so long and hard to develop. "SLS and Orion were purpose-designed to do this mission," says Pam Melroy, NASA deputy administrator. "It's designed to take a huge amount of cargo and people to deep space. Therefore, it's not something we're going to walk away from." ■



AI COMPUTING COMES TO MEMORY CHIPS

Samsung will double performance of neural nets with processing-in-memory

BY SAMUEL K. MOORE

Samsung added AI compute cores to DRAM memory dies to speed up machine learning.

JOHN VON NEUMANN'S original computer architecture, where logic and memory are separate domains, has had a good run. But some companies are betting that it's time for a change.

In recent years, the shift toward more parallel processing and a massive increase in the size of neural networks mean processors need to access more data from memory more quickly. And yet "the performance gap between DRAM and processor is wider than ever," says Joungho Kim, an expert in 3D memory chips at Korea Advanced Institute of Science and Technology, in Daejeon, and an IEEE Fellow. The von Neumann architecture has become the von Neumann bottleneck.

What if, instead, at least some of the processing happened in the memory? Less data would have to move between chips, and you'd save energy, too. It's not a new idea. But its moment may finally have arrived. Last year, Samsung, the world's largest maker of dynamic random-access memory (DRAM), started rolling out processing-in-memory (PIM) tech. Its first PIM offering, unveiled in February 2021, integrated AI-focused compute cores inside its Aquabolt-XL high-bandwidth memory. HBM is the kind of specialized DRAM that surrounds some top AI accelerator chips. The new memory is designed to act as a "drop-in replacement" for ordinary HBM chips, said Nam Sung Kim, an IEEE Fellow, who was then senior vice president of Samsung's memory business unit.

Last August, Samsung revealed results from tests in a partner's system. When used with the Xilinx Virtex Ultrascale+ (Alveo) AI accelerator, the PIM tech delivered a nearly 2.5-fold performance gain and a 62 percent cut in energy consumption for a speech-recognition neural net. Samsung has been providing samples of the technology integrated into the current generation of high-bandwidth DRAM, HBM2. It's also developing PIM for the next generation, HBM3, and for the low-power DRAM used in mobile devices. It expects to complete the standard for the latter with JEDEC in the first half of 2022.

THERE ARE PLENTY of ways to add computational smarts to memory chips. Samsung chose a design that's fast and simple. HBM consists of a stack of DRAM chips linked vertically by interconnects

SAMSUNG

called through-silicon vias (TSVs). The stack of memory chips sits atop a logic chip that acts as the interface to the processor.

The highest data bandwidth in the stack lies within each chip, followed by the TSVs, and finally the connections to the processor. So Samsung chose to put the processing on the DRAM chips to take advantage of the high bandwidth there. The compute units are designed to do the most common neural-network calculation, called multiply and accumulate, and little else. Other designs have put the AI logic on the interface chip or used more complex processing cores.

Samsung's two largest competitors, SK hynix and Micron Technology, aren't quite ready to take the plunge on PIM for HBM, though they've each made moves toward other types of processing-in-memory.

Icheon, South Korea–based SK hynix, the No. 2 DRAM supplier, is exploring PIM from several angles, says Il Park, vice president and head of memory-solution product development. For now it is pursuing PIM in standard DRAM chips rather than HBM, which might be simpler for customers to adopt, says Park.

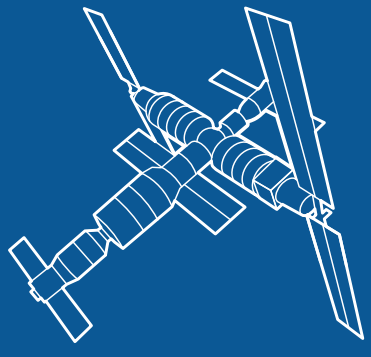
HBM PIM is more of a mid- to long-term possibility, for SK hynix. At the moment, customers are already dealing with enough issues as they try to move HBM DRAM physically closer to processors. "Many experts in this domain do not want to add more, and quite significant, complexity on top of the already busy situation involving HBM," says Park.

That said, SK hynix researchers worked with Purdue University computer scientists on a comprehensive design of an HBM-PIM product called Newton in 2019. Like Samsung's Aquabolt-XL, it places multiply-and-accumulate units in the memory banks to take advantage of the high bandwidth within the dies themselves.

Meanwhile, Rambus, based in San Jose, Calif., was motivated to explore PIM because of power-consumption issues, says Rambus fellow and distinguished inventor Steven Woo. The company designs the interfaces between processors and memory, and two-thirds of the power consumed by system-on-chip and its HBM memory go to transporting data horizontally between the two chips. Transporting data vertically within the HBM uses much less energy because the distances are so much shorter. "You might be going 10 to 15 millimeters horizontally to get data back to an SoC," says Woo. "But vertically you're talking on the order of a couple hundred microns."

Rambus's experimental PIM design adds an extra layer of silicon at the top of the HBM stack to do AI computation. To avoid the potential bandwidth bottleneck of the HBM's central through-silicon vias, the design adds TSVs to connect the memory banks with the AI layer. Having a dedicated AI layer in each memory chip could allow memory makers to customize memories for different applications, argues Woo.

How quickly PIM is adopted will depend on how desperate the makers of AI accelerators are for the memory-bandwidth relief it provides. "Samsung has put a stake in the ground," says Bob O'Donnell, chief analyst at Technalysis Research. "It remains to be seen whether [PIM] becomes a commercial success." ■



A Permanent Space Station for China

CHINA IS SCHEDULED to complete its Tiangong ("Heavenly Palace") space station in 2022. The station, China's first long-term space habitat, was preceded by the Tiangong-1 and Tiangong-2 stations, which orbited from 2011 to 2018 and 2016 to 2019, respectively. The new station's core module, the Tianhe, was launched in April 2021. A further 10 missions by the end of 2022 will deliver other components and modules, with construction to be completed in orbit. The final station will have two laboratory modules in addition to the core module. Tiangong will orbit at roughly the same altitude as the International Space Station but will be only about one-fifth the mass of the ISS.

—Michael Koziol

Illustration by MCKIBILLO

A BITCOIN WALLET FOR THE MASSES

Square simplified credit-card transactions. Now it wants to build cryptocurrency hardware

BY TEKLA S. PERRY

A WALLET to hold bitcoins—or other cryptocurrencies—is not at all a new idea. Basically a souped-up flash drive, these gadgets hold a private key, protected by a pin or passcode, that allows a user to securely access cryptocurrency data; the data itself lives in the blockchain. Some of these "wallets" have their own displays, some require use with a computer or phone.

Most wallets support a variety of cryptocurrencies—indeed, they are targeted at people who trade in multiple currencies and manage multiple keys. They make doing so a little easier, but they don't make cryptocurrencies useful for the rest of us.

Enter Square, the company that developed a little white dongle for smartphones that lets anyone easily accept credit-card payments.

"We're making a hardware wallet for the next 100M bitcoin users," the company wrote in a recent recruitment posting. "Our goal is economic empowerment, starting with bringing easy-to-use, reliable self-custody to a global audience."

Square first unveiled its hardware wallet plans in a series of tweets in June, the first coming from Square CEO Jack Dorsey. "Square is considering making a hardware wallet for bitcoin. If we do it, we would build it entirely in the open, from software to hardware design, and in collaboration with the community," he said in the tweet. (The company declined to comment further for this article.)

Since then, Square has listed jobs for the project on multiple recruitment sites; the company has been on the hunt for project managers, engineers, supply-chain managers, software developers, security experts, and other professionals to work on the wallet. And in December, the company changed its corporate name to "Block."

THIS ISN'T SQUARE'S—Block's—first foray into cryptocurrency. In late 2018, the company expanded its mobile payments platform, Cash App, to include the ability to buy and sell bitcoins, as well as to send them to other Cash App users. Square initially charged a fee for these transactions, but it recently dropped the fee and now makes a profit by acting as its own exchange, with slightly different pricing for buy and sell transactions.

An app is not a hardware wallet, however. Apps leave users' private keys in the cloud—and there have been a number of incidents in which hackers managed to get into such online cryptocurrency accounts. Storing private keys offline, in a hardware wallet,

Photo-illustration by Edmon de Haro

significantly increases security but raises complexity for the user. Square CEO Dorsey indicated that Square's hardware wallet will use what he calls "assisted self-custody" to have the best of both worlds, security and simplicity.

Dorsey has been an unabashed fan of Bitcoin since its earliest days. "Bitcoin changes absolutely everything," he told attendees of the Bitcoin 2021 Conference. "I don't think there is anything more important in my lifetime to work on."

He is all-in on bitcoins versus other cryptocurrency, because, he tweeted in 2019, "Bitcoin is resilient. Bitcoin is principled. Bitcoin is native to internet ideals."

So unlike existing hardware wallets like the Ledger Nano X, the Trezor Model T, and the KeepKey, Square's wallet won't support multiple cryptocurrencies, only bitcoins. Dorsey wants Bitcoin to become *the* standard cryptocurrency, leaving Tether, Ethereum, Binance, Ripple, and dozens of other popular alternatives in the dust. His hardware-wallet move just might be the accelerant Bitcoin needs to do that.

WHEN WILL ALL this happen? Look for this crypto gadget in the second half of the year, says Dan Dolev, managing director and senior analyst for fintech equity research at Mizuho, a global banking and financial services company.

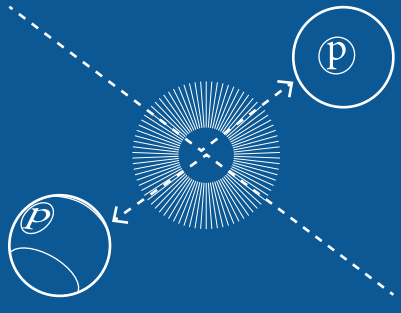
And it won't just be another memory stick, says Dolev. He likened Square's announcement to Apple's entry into the smartphone market. "Before the iPhone's introduction in 2007, there were a bunch of smartphones out there that connected to the Internet, like the Palm Pilot and the Blackberry. And they worked fine. But there wasn't a sense of an ecosystem. Same thing with hardware wallets."

With Square's involvement, he says, "we know it's not just going to be a key that stores bitcoin passwords; it's going to be something people can use for more. Maybe it will be like a debit card, maybe something else. Square's end goal is to create a global network of decentralized finance on top of the Bitcoin blockchain."

It isn't going to be easy. People will want it to purchase things in the real world, not just to buy, sell, and hold cryptocurrencies. As it was with the development of near-field-communication (NFC) payments, the hardware is not the problem. Rather, Dolev says, the challenge will involve working with merchants to accept the currency and figuring out how to bring down transaction costs.

And while nobody knows exactly what this gadget will look like, its basic shape will probably be a square, of course. Or, says Dolev, "even more likely, a block."

"I wouldn't underestimate Square's ability to succeed here," he says. "Everything they've touched, historically, has turned into gold." ■

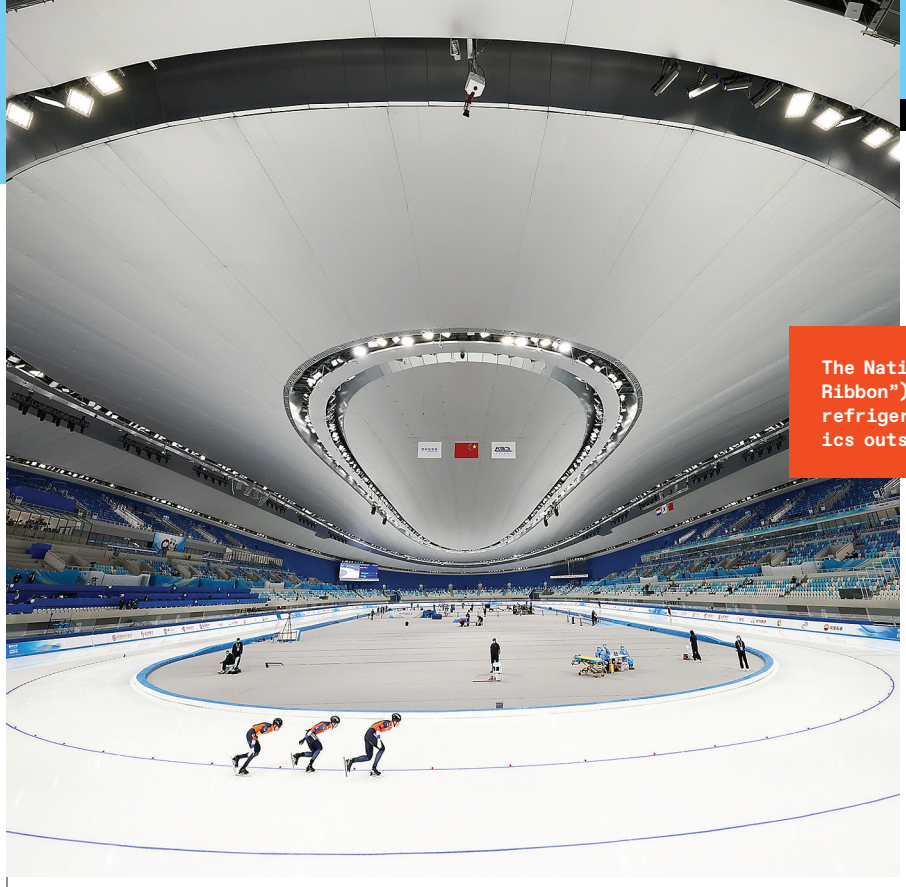


New Dark-Matter Detector

THE FORWARD SEARCH Experiment (FASER) at CERN will switch on in July 2022. The exact date depends on when the Large Hadron Collider is set to renew proton-proton collisions after three years of planned upgrades and maintenance. FASER will begin a hunt for dark matter and other particles that interact extremely weakly with "normal" matter. CERN, the fundamental physics research center near Geneva, has four main detectors attached to its Large Hadron Collider, but they aren't well-suited to detecting dark matter. FASER won't attempt to detect the particles directly; instead, it will search for the more strongly interacting Standard Model particles created when dark matter interacts with something else. The new detector was constructed while the collider was shut down from 2018 to 2021. Located 480 meters "downstream" of the ATLAS detector, FASER will also hunt for neutrinos produced in huge quantities by particle collisions in the LHC loop. The other CERN detectors have so far failed to detect such neutrinos.

—Michael Koziol

Illustration by MCKIBILLO



The National Speed Skating Oval ("The Ice Ribbon") in Beijing uses climate-friendly refrigeration to make ice and photovoltaics outside to generate electricity.

LINTAO ZHANG/GETTY IMAGES

CHINA'S GREEN WINTER OLYMPICS

A variety of climate-friendly strategies will be on show, along with the athletes

BY PRACHI PATEL

About 160 kilometers northwest of Beijing, the city of Zhangjiakou with its rugged terrain boasts some of the richest wind and solar resources in China. Renewables account for nearly half of the city's electricity output—and that's with less than a third of its full solar and wind potential of 70 gigawatts installed so far.

That makes it an ideal cohost with Beijing for the 2022 Winter Olympic and Paralympic Games, which China plans to make the greenest yet. The plan is to power all 26 venues fully with renewables, marking a first in the games' history.

The Beijing 2022 Organising Committee aims to make the games carbon neutral, or as close as possible—a benchmark for the International Olympic Committee's mission to make the Olympics climate positive by 2024.

Besides being a symbol for President Xi Jinping's ambitious goal of China being carbon neutral by 2060, the 2022 games should drive sustainable development in the region. The event has already helped Beijing clean up its skies and environment, and has fired up local energy-technology markets. It will also be a global stage to showcase new energy-efficiency, alternate-transport, and refrigeration technologies.

The Olympics will use a tiny fraction of the country's electricity. Powering them cleanly won't be hard given China's plentiful renewable capacity, says Michael Davidson, an engineering-systems and global-policy expert at the University of California, San Diego.

But Davidson also points out that insufficient infrastructure to manage intermittent renewables and electricity-dispatch practices that don't prioritize them mean that much of China's green-power capacity is often not put to use. And because the game venues are connected to a grid powered by many sources, asserting that all the electricity used at the games is 100 percent from clean energy sources is "complicated," he says. Nonetheless, the games will be important in raising the profile of green energy. "The hope is that this process will put into place some institutions that could help leverage a much broader-scale move to green."

Case in point: The flexible DC grid put into place in Zhangjiakou in 2020 will let 22.5 billion kilowatt-hours of wind and solar energy flow from Zhangjiakou to Beijing every year. By the time the

Paralympics end in March, the game venues are expected to have consumed about 400 million kWh of electricity. Providing all of it by renewables should reduce carbon emissions by 320,000 tonnes, according to sports outlet Inside the Games. After the athletes go home, the flexible DC grid will continue to clean up around 10 percent of the capital's immense electricity consumption.

GREEN-TRANSPORT infrastructure being built to shuttle athletes and spectators between venues will also be part of the games' lasting legacy. A clean energy–powered high-speed railway that takes 47 minutes to travel between Beijing and Zhangjiakou was inaugurated in 2019. More than 85 percent of public-transport vehicles at the Olympics will be powered by batteries, hydrogen fuel cells, or natural gas, according to state media.

In August, Beijing officials revealed their plans to build 37 fueling stations and have about 3,000 fuel-cell vehicles on the road by 2023, for which the Olympics should also be a stepping-stone. Already, hydrogen fueling stations built by China's petrochemical giant Sinopec, Pennsylvania-based Air Products, and French company Air Liquide have cropped up in Beijing, Zhangjiakou, and the Yanqing competition zone located in between.

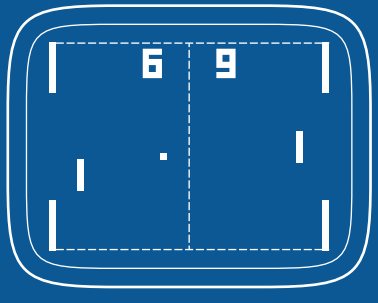
In Yanqing alone, 212 fuel-cell buses made by Beijing-based Beiqi Foton Motor Co. will shuttle spectators around. Even the iconic Olympic torch will burn hydrogen for its flame.

The 2022 event will also put a limelight on climate-friendly refrigeration. The immense 12,000-square-meter speed-skating oval in downtown Beijing—8 times the size of a hockey rink—will be the first in the world to use carbon dioxide for making ice.

"We've built skating rinks with carbon dioxide direct cooling but never a speed-skating oval," says Wayne Dilk of Toronto-based refrigeration company CIMCO Refrigeration, which has built most of the National Hockey League arenas in North America and designed and provided consulting services for the Olympics' icy venues.

Ice rinks typically rely on refrigerants siphoning heat away from brine circulated under the floors, Dilk explains. But CO_2-based cooling systems, which are getting more popular mainly in Europe and North America for supermarkets, food-manufacturing plants, and ice rinks, use CO_2 both as the refrigerant and for transporting heat away from under the floor where it is pumped in liquid form.

CO_2 is a climate villain, of course, but conventional hydrofluorocarbon refrigerants are worse. The common R-22 form of Freon, for example, is about 1,800 times as potent as a greenhouse gas. CO_2-based cooling systems are also 30 percent more energy efficient than Freon, says Dilk. Plus, the CO_2 system produces higher-temperature waste heat, which can be used for space heating and hot water. And while the system is more expensive to build because it runs at higher pressure, the temperature across the large surface stays within a range of only 0.5 °C, giving more uniform ice. Consistent temperature and ice quality generate better competitive racing times. The Beijing 2022 hockey arenas and sliding center for bobsled and luge use climate-friendly ammonia or Opteon as refrigerants. Besides being a key part of the greenest Winter Olympics, these state-of-the-art ice venues should seal the deal for another goal China has in 2022: to establish itself as a world-class winter sports and tourism destination. ■



Pong Turns 50

ATARI CHANGED the course of video games when it released its first game, *Pong,* in 1972. While not the first video game—or even the first to be presented in an upright, arcade-style cabinet—*Pong* was the first to be commercially successful. The game was developed by engineer Allan Alcorn and originally assigned to him as a test after he was hired, before he began working on actual projects. However, executives at Atari saw potential in *Pong*'s simple game play and decided to develop it into a real product. Unlike the countless video games that came after it, the original *Pong* did not use any code or microprocessors. Instead, it was built from a television and transistor-transistor logic.

—Michael Koziol

Illustration by MCKIBILLO

PLANET-COOLING TESTS COULD START IN 2022

A controversial geoengineering plan aims to spray reflective particles into the stratosphere

BY MARIA GALLUCCI

THE STRATOSPHERE is a dry and frigid place, where the air is thin and clouds are scarce. Up there, 10 to 50 kilometers above the Earth's surface, ozone molecules absorb the sun's ultraviolet light, protecting life far below. This second layer of the atmosphere is serene and mostly void of life. It's also become the subject of one of today's most contentious scientific proposals.

The proposal calls for what's known as "solar geoengineering": cooling the planet by deflecting sunlight that would otherwise strike the planet. Later this year, researchers hope to release a balloon that will ascend to 20 km, where they'll test the airborne platform. Eventually, they'll add equipment to spray tiny aerosol particles of calcium carbonate, the compound found in limestone, blackboard chalk, and Tums antacids. The particles will act like microscopic mirrors that should reflect sunlight back into space.

Little is known about how, or whether, solar geoengineering might work and how the particles would react and move in the stratosphere. Even less is understood about the potential risks to people and the environment—could the particles deplete the ozone, for example, or significantly alter the weather? But as Earth's rising temperatures trigger a cascade of calamitous effects, and as humans pump more greenhouse gases into the air, a prominent group of scientists is urging the world to seriously consider the stratospheric option.

One of those scientists is Harvard University's Frank Keutsch, who is leading the high-profile Stratospheric Controlled Perturbation Experiment (SCoPEx). He says the group hopes to launch the balloon in mid-2022. Keutsch believes solar geoengineering's many unknowns are precisely why SCoPEx is worth doing. If global warming continues unabated, and the world veers toward catastrophe, it would be better to have tools ready to avoid the most dire outcomes, he says.

"Research takes a long time," says Keutsch, an atmospheric chemist. "If we only start research when people say, 'Oh, I think we need this,' then it's too late."

The SCoPEx data could help improve computer models, which today rely mainly on assumptions and predictions, not observations. The quantity of calcium carbonate to be released—about 1 kilogram—won't be enough to trigger any measurable cooling, and it roughly equals the particle pollution that a large commercial airliner releases every minute of flight, says David Keith, a physics and public-policy professor at Harvard who helps lead the project. (Keith is also the founder of Carbon Engineering, a Canadian firm building a sprawling facility in West Texas that will pull carbon dioxide directly from the air.)

Yet even this basic research is proving to be controversial. Critics say that pursuing solar geoengineering is a dangerous distraction from the more essential task of rapidly reducing greenhouse gas emissions. For many, the mere idea of humans intervening in the climate system is problematic and worth shutting down before it gains traction. The first SCoPEx test was originally planned for early 2021 in northern Sweden, but backlash from environmental and indigenous groups prompted the team to cancel the launch.

Still, Keutsch says he's optimistic that this year's test will go forward, once the researchers find a new balloon partner and launch site. "The more we learn about the reality of the state of climate change, there's a greater realization that this research is something we have to start sooner rather than later," he says.

Photo-illustration by Edmon de Haro

The first SCoPEx test was planned for an early 2021 launch from the Esrange Space Center in northern Sweden, but backlash prompted the team to cancel the launch.

SWEDISH SPACE CORP.

THE REALITY IS that the planet is warming at an alarming rate. Concentrations of greenhouse gases are at record levels, mostly because of the coal, oil, and natural gas that gets burned for electricity, heat, and transportation. Today, the average global temperature is about 1.09 °C hotter than in the late 19th century, according to the Intergovernmental Panel on Climate Change (IPCC), the United Nations–run scientific authority on global warming. "It is unequivocal that human influence has warmed the atmosphere, ocean, and land," the IPCC stated in a comprehensive report released in August.

Scientists warn that global warming is likely to hit 1.5 °C within the next two decades, a level that will bring devastating and long-term effects such as catastrophic flooding, severe drought, deadly heat waves, and mass die-offs of coral reefs. Humanity can still prevent further, more perilous levels of warming, the IPCC affirmed in its report. But doing so will require immediately shifting away from fossil fuels, scaling up renewable energy, and potentially even removing carbon dioxide from the atmosphere.

In this unnerving context, solar geoengineering could be a "painkiller" for the planet—not a substitute for curbing emissions or restoring carbon-trapping forests, but a balm that makes life on Earth more bearable in a sweltering future, Keutsch says.

Not everyone agrees. Painkillers can lead to harmful addictions, the U.S. climate scientist Michael E. Mann has said. He has likened solar geoengineering to "climate methadone," because once the world starts injecting sun-dimming particles, it likely won't be able to stop.

HARVARD SCIENTISTS first proposed SCoPEx in a 2014 research paper. They called for "small-scale, *in situ* experimentation" that could help remove some of the uncertainties and "unknown unknowns" surrounding solar geoengineering, which in the paper they called solar-radiation management.

The proposal didn't gain momentum until 2017, when Keith, a coauthor of the 2014 paper, became faculty director of Harvard's Solar Geoengineering Research Program. The program, of which SCoPEx is the centerpiece, has so far raised US $16.2 million from Microsoft cofounder Bill Gates, the William and Flora Hewlett Foundation, and

other philanthropic organizations.

SCoPEx has two main goals: to observe how plumes of particles disperse in the stratosphere, and to explore which types of particles have the fewest side effects.

This year's field experiment will be carried aloft by a zero-pressure balloon that stretches 27 meters in diameter, roughly the length of two school buses. The balloon isn't particularly novel; every year, NASA conducts up to 15 stratospheric balloon flights to collect data and test technologies for space missions.

What's unique is SCoPEx's gondola, an aluminum and carbon-fiber frame that holds an array of hardware. A Raspberry Pi 4–based flight computer will receive commands and log data. Two Globalstar satellite phones will enable communication between the gondola and ground equipment. Twin airboat propellers will move the airborne gondola horizontally and vertically.

During its first flight, SCoPEx will test how well the platform operates when exposed to temperatures down to −60 °C as well as direct sunlight. Although researchers can simulate the stratosphere in a thermal vacuum chamber, it's difficult to know how real-world conditions will affect equipment. The gondola won't carry any chemicals or particle-spraying tools on this initial test, which will last 4 to 6 hours at an altitude of nearly 20 km—more than twice the height of Mount Everest.

Assuming the gondola passes muster, the next test will be to spray and track particles in the stratosphere. A spraying device will release the calcium carbonate into a kilometer-long wake created by the propellers. The balloon will then move back and forth through the wake, while lidar tracks how far the particle plume travels. A lightweight Portable Optical Particle Spectrometer will measure the size and number of particles. Other equipment will collect data on the moisture and ozone in the stratosphere.

"This is not a test of whether solar geoengineering works," Keith says. "These are things we need to do if we're going to improve the science of solar geoengineering." SCoPEx will allow researchers to evaluate potential side effects, which could be significant, including possible ozone depletion, increased air pollution, and changes in weather patterns, with some regions likely to be more negatively affected than others.

The key question for society, he says, is whether the risks of solar geoengineering are worth taking, to avoid the extreme consequences of global warming. "We don't face a risk-free decision," Keith says. "The issue is about risk trade-offs."

THE STALLED 2021 launch highlighted questions about solar geoengineering research—how or whether it should occur, and who gets to decide. As it stands, a small number of researchers from wealthy Western institutions are contemplating an approach that, if deployed, could potentially impact everyone on Earth. There's no agency to build a global consensus or provide oversight. Indeed, the National Academies of Sciences,

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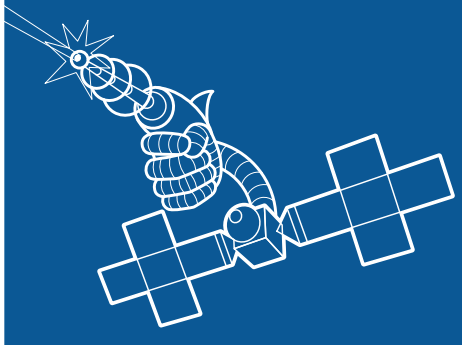


Psyche's Deep-Space Lasers

IN AUGUST, NASA will launch the Psyche mission, sending a deep-space orbiter to a weird, metal asteroid orbiting between Mars and Jupiter. While the probe's main purpose is to study Psyche's origins, it will also carry an experiment that could inform the future of deep-space communications. The Deep Space Optical Communications (DSOC) experiment will test whether lasers can transmit signals beyond lunar orbit. Optical signals, such as those used in undersea fiber-optic cables, can carry more data than radio signals can, but their use in space has been hampered by difficulties in aiming the beams accurately over long distances. DSOC will use a 4-watt infrared laser with a wavelength of 1,550 nanometers (the same used in many optical fibers) to send optical signals at multiple distances during Psyche's outward journey to the asteroid.

—Michael Koziol

Illustration by MCKIBILLO

A ROBOT FOR THE WORST JOB IN THE WAREHOUSE

Boston Dynamics' Stretch can move 800 heavy boxes per hour

BY EVAN ACKERMAN

AS COVID-19 stresses global supply chains, the logistics industry is looking to automation to help keep workers safe and boost their efficiency. But there are many warehouse operations that don't lend themselves to traditional automation—namely, tasks where the inputs and outputs of a process aren't always well defined and can't be completely controlled. A new generation of robots with the intelligence and flexibility to handle the kind of variation that people take in stride is entering warehouse environments. A prime example is Stretch, a new robot from Boston Dynamics that can move heavy boxes where they need to go just as fast as an experienced warehouse worker.

Stretch's design is somewhat of a departure from the humanoid and quadrupedal robots that Boston Dynamics is best known for, such as Atlas and Spot. With its single massive arm, a gripper packed with sensors and an array of suction cups, and an omnidirectional mobile base, Stretch can transfer boxes that weigh as much as 50 pounds (23 kilograms) from the back of a truck to a conveyor belt at a rate of 800 boxes per hour. An experienced human worker can move boxes at a similar rate, but not all day long, whereas Stretch can go for 16 hours before recharging. And this kind of work is punishing on the human body, especially when heavy boxes have to be moved from near a trailer's ceiling or floor.

"Truck unloading is one of the hardest jobs in a warehouse, and that's one of the reasons we're starting there with Stretch," says Kevin Blankespoor, senior vice president of warehouse robotics at Boston Dynamics. Blankespoor explains that Stretch isn't meant to replace people entirely; the idea is that multiple Stretch robots could make a human worker an order of magnitude more efficient. "Typically, you'll have two people unloading each truck. Where we want to get with Stretch is to have one person unloading four or five trucks at the same time, using Stretches as tools."

ALL STRETCH NEEDS is to be shown the back of a trailer packed with boxes, and it'll autonomously go to work, placing each box on a conveyor belt one by one until the trailer is empty. People are still there to make sure that everything goes smoothly, and they can step in if Stretch runs into something that it can't handle, but their full-time job becomes robot supervision instead of lifting heavy boxes all day.

Achieving this level of reliable autonomy with Stretch has taken Boston Dynamics years of work, building on decades of experience developing robots that are strong, fast, and agile. Besides the challenge of building a high-performance robotic arm, the company also had to solve some problems that people find trivial but are difficult for robots, like looking at a wall of closely packed brown boxes and being able to tell where one stops and another begins.

Safety is also a focus, says Blankespoor, explaining that Stretch follows the standards for mobile industrial robots set by the American National Standards Institute and the Robotics Industry Association. That the robot operates inside a truck or trailer also helps to keep

Stretch can autonomously transfer boxes onto a roller conveyor fast enough to keep up with an experienced human worker.

Stretch safely isolated from people working nearby, and at least for now, the trailer opening is fenced off while the robot is inside.

Stretch is optimized for moving boxes, a task that's required throughout a warehouse. Boston Dynamics hopes that over the longer term the robot will be flexible enough to put its box-moving expertise to use wherever it's needed. In addition to unloading trucks, Stretch has the potential to unload boxes from pallets, put boxes on shelves, build orders out of multiple boxes from different places in a warehouse, and ultimately load boxes onto trucks, a much more difficult problem than unloading due to the planning and precision required.

In the short term, unloading a trailer (part of a warehouse job called "receiving") is the best place for a robot like Stretch, agrees Matt Beane, who studies work involving robotics and AI at the University of California, Santa Barbara. "No one wants to do receiving," he says. "It's dangerous, tiring, and monotonous."

But Beane, who for the last two years has led a team of field researchers in a nationwide study of automation in warehousing, points out that there may be important nuances to the job that a robot such as Stretch will probably miss, like interacting with the people who are working other parts of the receiving process. "There's subtle, high-bandwidth information being exchanged about boxes that humans down the line use as key inputs to do their job effectively, and I will be singularly impressed if Stretch can match that."

Boston Dynamics spent much of 2021 turning Stretch from a prototype, built largely from pieces designed for Atlas and Spot, into a production-ready system that will begin shipping to a select group of customers in 2022, with broader sales expected in 2023. For Blankespoor, that milestone will represent just the beginning. He feels that such robots are poised to have an enormous impact on the logistics industry. "Despite the success of automation in manufacturing, warehouses are still almost entirely manually operated—we're just starting to see a new generation of robots that can handle the variation you see in a warehouse, and that's what we're excited about with Stretch." ■

Photo by Bob O'Connor

QUANTUM DOTS + OLED = YOUR NEXT TV

Formerly rival technologies will come together in new Samsung displays

BY PETER PALOMAKI

FOR MORE THAN a decade now, OLED (organic light-emitting diode) displays have set the bar for screen quality, albeit at a price. That's because they produce deep blacks, offer wide viewing angles, and have a broad color range. Meanwhile, QD (quantum dot) technologies have done a lot to improve the color purity and brightness of the more wallet-friendly LCD TVs.

In 2022, these two rival technologies will merge. The name of the resulting hybrid is still evolving, but QD-OLED seems to make sense, so I'll use it here, although Samsung has begun to call its version of the technology QD Display.

To understand why this combination is so appealing, you have to know the basic principles behind each of these approaches to displaying a moving image.

In an LCD TV, the LED backlight, or at least a big section of it, is on all at once. The picture is created by filtering this light at the many individual pixels. Unfortunately, that filtering process isn't perfect, and in areas that should appear black some light gets through.

In OLED displays, the red, green, and blue diodes that comprise each pixel *emit* light and are turned on only when they are needed. So black pixels appear truly black, while bright pixels can be run at full power, allowing unsurpassed levels of contrast.

But there's a drawback. The colored diodes in an OLED TV degrade over time, causing what's called "burn-in." And with these changes happening at different rates for the red, green, and blue diodes, the degradation affects the overall ability of a display to reproduce colors accurately as it ages and also causes "ghost" images to appear where static content is frequently displayed.

Adding QDs into the mix shifts this equation. Quantum dots—nanoparticles of semiconductor material—absorb photons and then use that energy to emit light of a different wavelength. In a QD-OLED display, all the diodes emit blue light. To get red and green, the appropriate diodes are covered with red or green QDs. The result is a paper-thin display with a broad range of colors that remain accurate over time. These screens also have excellent black levels, wide viewing angles, and improved power efficiency over both OLED and LCD displays.

Samsung is the driving force behind the technology, having sunk billions into retrofitting an LCD fab in Asan, South Korea, for making QD-OLED displays. While

Photo-illustration by Edmon de Haro

other companies have published articles and demonstrated similar approaches, only Samsung has committed to manufacturing these displays, which makes sense because it holds all of the required technology in house. Having both the OLED fab and QD expertise under one roof gives Samsung a big leg up on other QD-display manufacturers.

Samsung first announced QD-OLED plans in 2019, then pushed out the release date a few times. It now seems likely that we will see public demos in early 2022 followed by commercial products later in the year, once the company has geared up for high-volume production. At this point, Samsung can produce a maximum of 30,000 QD-OLED panels a month; these will be used in its own products. In the grand scheme of things, that's not that much.

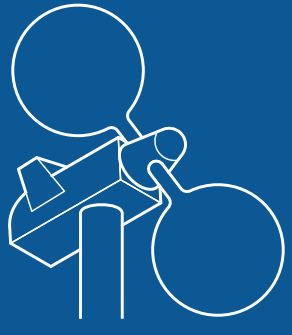
UNFORTUNATELY, as with any new display technology, there are challenges associated with development and commercialization.

For one, patterning the quantum-dot layers and protecting them is complicated. Unlike QD-enabled LCD displays (commonly referred to as QLED) where red and green QDs are dispersed uniformly in a polymer film, QD-OLED requires the QD layers to be patterned and aligned with the OLEDs behind them. And that's tricky to do. Samsung is expected to employ inkjet printing, an approach that reduces the waste of QD material.

Another issue is the leakage of blue light through the red and green QD layers. Leakage of only a few percent would have a significant effect on the viewing experience, resulting in washed-out colors. If the red and green QD layers don't do a good job absorbing all of the blue light impinging on them, an additional blue-blocking layer would be required on top, adding to the cost and complexity.

Another challenge is that blue OLEDs degrade faster than red or green ones do. With all three colors relying on blue OLEDs in a QD-OLED design, this degradation isn't expected to cause the severe color shifts that occur with traditional OLED displays, but it does decrease brightness over the life of the display.

Today, OLED TVs are typically the most expensive option on retail shelves. And while the process for making QD-OLED simplifies the OLED layer somewhat (because you need only blue diodes), it does not make the display any less expensive. In fact, due to the large number of quantum dots used, the patterning steps, and the special filtering required, consumers can expect QD-OLED TVs to sell for more than OLED TVs, at least initially, and much more than LCD TVs with quantum-dot color purification. Early adopters may pay about US $5,000 for the first QD-OLED displays when they begin selling later this year. Those buyers will no doubt complain about the prices—while enjoying a viewing experience far better than anything they've had before. ■



The Green Hydrogen Boom

UTILITY COMPANY Energias de Portugal (EDP), based in Lisbon, is on track to begin operating a 3-megawatt green-hydrogen plant in Brazil by the end of the year. Green hydrogen is hydrogen produced in sustainable ways, using solar or wind-powered electrolyzers to split water molecules into hydrogen and oxygen. According to the International Energy Agency, only 0.1 percent of hydrogen is produced this way. The plant will replace an existing coal-fired plant and generate hydrogen—which can be used in fuel cells—using solar photovoltaics. EDP's roughly US $7.9 million pilot program is just the tip of the green-hydrogen iceberg. Enegix Energy has announced plans for a $5.4 billion green-hydrogen plant in the same Brazilian state, Ceará, where the EDP plant is being built. The green-hydrogen market is predicted to generate a revenue of nearly $10 billion by 2028, according to a November 2021 report by Research Dive.

—Michael Koziol

Illustration by MCKIBILLO

In Zap Energy's FuZE-Q demonstration reactor, slated for completion in mid-2022, the column of plasma is surrounded and contained by faster-flowing plasma.

A PINCH OF FUSION

Zap Energy's new Z-pinch reactor will demonstrate a simpler approach to an elusive goal

BY TOM CLYNES

TOKAMAKS, which use magnets to contain the high-temperature plasma in which atomic nuclei fuse and release energy, have captured the spotlight in recent months, due to tremendous advances in superconducting magnets. Despite these gains, though, traditional magnetic-confinement fusion is still years away from fulfilling nuclear fusion's promise of generating abundant and carbon-free electricity.

But tokamaks aren't the only path to fusion power. Seattle-based Zap Energy's FuZE-Q reactor, scheduled to be completed in mid-2022, bypasses the need for costly and complex magnetic coils. Instead, the machine sends pulses of electric current along a column of highly conductive plasma, creating a magnetic field that simultaneously confines, compresses, and heats the ionized gas. This Z-pinch approach—so named because the current pinches the plasma along the third, or *Z*, axis of a three-dimensional grid—could potentially produce energy in a device that's simpler, smaller, and cheaper than the massive tokamaks or laser-fusion machines under development today.

Z-pinched plasmas have historically been plagued by instabilities. In the absence of a perfectly uniform squeeze, the plasma wrinkles and kinks and falls apart within tens of nanoseconds—far too short to produce useful amounts of electricity.

Zap Energy's approach, which it calls sheared-flow stabilization, tames these instabilities by varying the flow of plasma along the column. The design sheathes the plasma near the column's central axis with faster-flowing plasma—imagine a steady stream of cars traveling in the center lane of a highway, unable to change lanes because heavy traffic is whizzing by on both sides. That arrangement keeps the fusion-reactive plasma corralled and compressed longer than previous Z-pinch configurations could.

"We think our reactor is the least expensive, most compact, most scalable solution with the shortest path to commercially viable fusion power," says Ben Levitt, Zap Energy's director of research and development. Levitt predicts that Zap will reach Q=1, or scientific breakeven—the point at which the energy released by the fusing atoms is equal to the energy required to create the conditions for fusion—by mid-2023, which would make it the first fusion project to do so.

Given the long history of broken promises in fusion-energy research, that's the sort of claim that warrants skepticism. But Zap's ascent of a forbiddingly steep technology curve has been swift and impressive. The startup was

ZAP ENERGY

founded in 2017 as a spin-off of the FuZE (Fusion Z-pinch Experiment) research team at the University of Washington. The company produced its first fusion reactions the very next year. Before the company's founding, the university team had collaborated with Lawrence Livermore National Laboratory researchers. They won a series of U.S. Department of Energy grants that enabled them to test the sheared-flow approach at progressively higher energy levels. To date, the company has raised more than US $40 million.

Thus far, experiments have confirmed simulations that predict the plasma will stay stable as Z-pinch currents are amped up. The new machine, budgeted to cost about $4 million, will dial up the strength of the pulses from 500 kiloamperes to more than 650 kA—the approximate threshold at which Levitt and his team believe they can demonstrate breakeven.

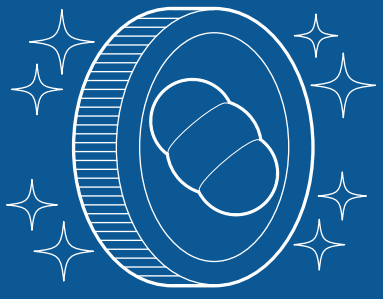
"Will the plasma stay stable as we keep increasing the energy we're putting into it? That's the trillion-dollar question," Levitt says. "We have lots of high-fidelity simulations showing that the physics doesn't change, that the sheared-flow mechanism works as we go to higher inherent energy. But we need proof, and we're not that far away."

THE REAL WORLD has often made a mockery of the most confident simulation-based predictions—especially in plasma physics, where unexpected instabilities tend to pop up with the slightest change in conditions. And even if the new FuZE-Q machine achieves scientific breakeven, it will be left to a future machine to produce the even higher currents necessary to surpass *engineering* breakeven, where the electric power at the output exceeds what's needed to produce the fusion reaction. Zap hopes to reach that milestone in 2026.

"Going back decades, a lot of teams have tried to make the Z-pinch approach work, and now Zap has found a way to stabilize it with the sheared flow," says Matt Moynihan, a former nuclear engineer for the U.S. Navy and a fusion consultant. "It's exciting that it's working under the conditions they've tested, but now we'll need to see if that stability holds when they scale up the power enough to get net energy out of it."

What no one disputes is the critical need for a carbon-free, always-available electricity source. Nuclear fusion could be it, but mainstream approaches are too costly and advancing too slowly to make an impact on the climate crisis. Zap's reactor could also be applied someday to advanced space propulsion. Attached to a spacecraft, the end of a Z-pinch reactor could be left open to allow the fast-moving plasma to escape, releasing a jet of material that could propel a spacecraft forward.

At this point, both fusion-powered space flight and fusion-powered electricity remain in the theoretical realm—but Zap Energy is aiming for the stars. ■

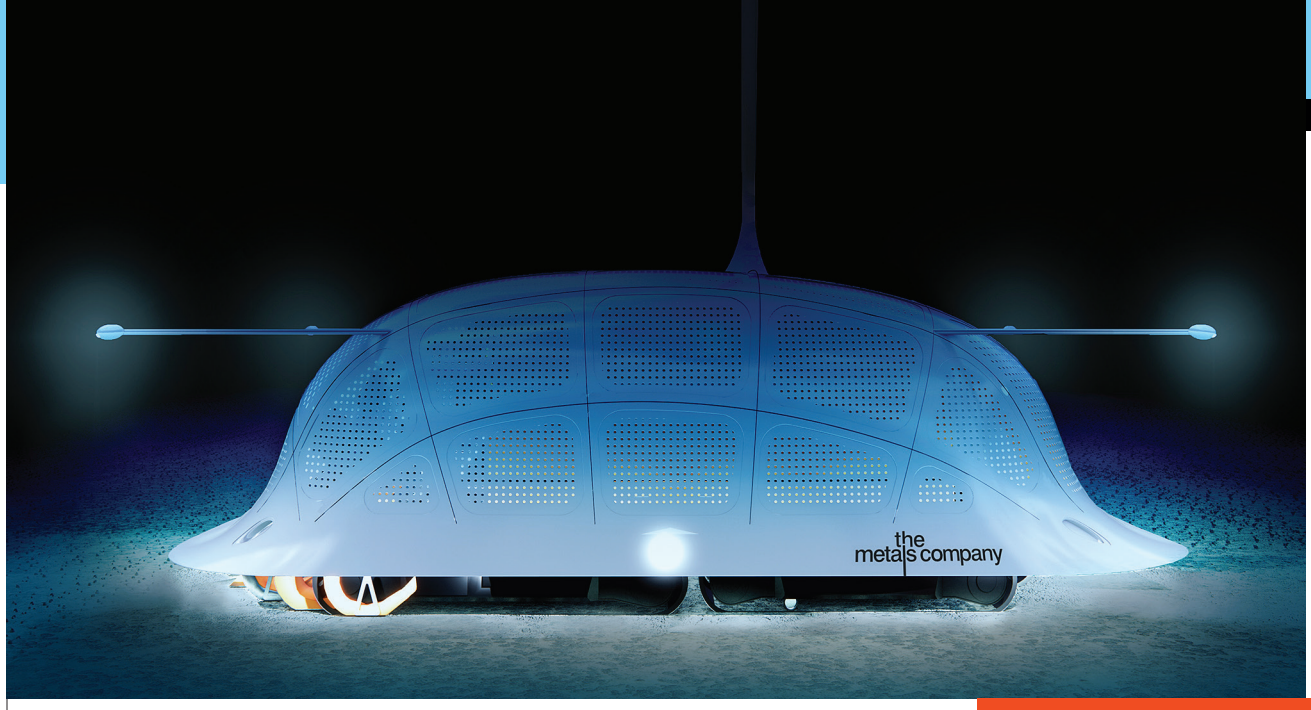


Greener Crypto-currency?

SEATTLE-BASED startup Nori is set to offer a cryptocurrency for carbon removal. Nori will mint 500 million tokens of its Ethereum-based currency (called NORI). Individuals and companies can purchase and trade NORI, and eventually exchange any NORI they own for an equal number of carbon credits. Each carbon credit represents a tonne of carbon dioxide that has *already* been removed from the atmosphere and stored in the ground. When exchanged in this way, a NORI is retired, making it impossible for owners to try to "double count" carbon credits and therefore seem like they're offsetting more carbon than they actually have. The startup has acknowledged that Ethereum and other blockchain-based technologies consume an enormous amount of energy, so the carbon it sequesters could conceivably originate in cryptocurrency mining. However, 2022 will also see Ethereum scheduled to switch to a much more energy-efficient method of verifying its blockchain, called proof-of-stake, which Nori will take advantage of when it launches.

—Michael Koziol

Illustration by MCKIBILLO



The Metals Company will outfit its nodule-collection robot with lights and cameras, which will document its effects on the ocean floor.

DEEP-SEA MINING STIRS UP MUDDY QUESTIONS

A controversial pilot program will collect metal-rich nodules from the ocean floor

BY DAVID SCHNEIDER

LAST MARCH, BMW and Volvo joined other companies calling for a moratorium on deep-sea mining, one spearheaded by the World Wildlife Fund. The addition of these two carmakers' names was significant because the battery in an electric vehicle contains at least a few kilograms of cobalt, a metal that some hope one day to extract from the seabed—to the chagrin of many environmentalists.

This simmering controversy will no doubt reach the boiling point in 2022, when the Metals Company begins testing a system for collecting metal-rich nodules from the ocean floor. Most press coverage of this will no doubt paint a simplistic picture of the arguments for and against doing so. But the question of whether obtaining cobalt and other valuable metals from the ocean floor would help or hurt the environment overall is, in fact, quite complicated.

A reasoned judgement will hinge on many things, including how much you are concerned by the toll from conventional mining. More than half of the world's cobalt currently comes from the Democratic Republic of the Congo, which has had a dismal record for protecting the environment and the well-being of the people who live and work around its mines.

Would having another large source available—the deep Pacific—help corporate buyers pressure Congolese mining companies to clean up their act? This and other important questions will remain open for some time, but one critical component in the calculus—the degree of environmental disruption involved in collecting metal-rich nodules from the deep Pacific—should become much clearer after the Metals Company begins pilot operations in the Pacific later this year.

THOSE OPERATIONS will be conducted from what formerly served as a petroleum drill ship, rechristened *Hidden Gem*. The giant vessel is now being outfitted to collect polymetallic nodules, which are gravel- to briquette-size concretions that can be found strewn almost like paving stones on certain parts of the deep-ocean floor. Unlike some other strategies for obtaining metal ores from the seafloor, getting them from

THE METALS COMPANY

nodules is more a matter of collecting than "mining" in the usual sense of the word.

Sometime in 2022, workers on the *Hidden Gem* will lower into the water a steel pipe of colossal proportions, one segment at a time, with a total length of 4 kilometers. But it won't simply dangle over the seafloor, hoovering up nodules like a giant underwater vacuum cleaner.

"At the business end is the robotic collector vehicle," explains Jon Machin, head of offshore engineering at the Metals Company. This vehicle is some 12 meters long and weighs 80 tonnes in air. In water, though, it weighs significantly less—just enough for the vehicle to gain traction as it propels itself, but not so much as to cause it to get mired in the mud.

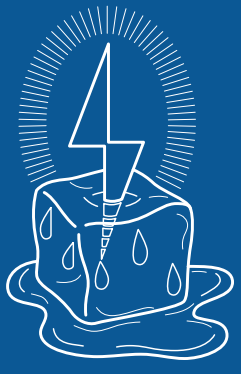
A flexible conduit will connect the end of the steel pipe with the vehicle. As the vehicle moves over the bottom, it will funnel nodules through this flexible conduit and into the pipe, where they will be sent upward using what Machin calls "an air-lift system": Compressed air injected into the bottom of the pipe will create countless bubbles, which will help raise the nodules, along with some mud and seawater.

Nodules will be separated from this slurry aboard the *Hidden Gem*, which will store them in its hold and discard what remains. The best depth to discharge the leftovers is not yet entirely clear. Doing so in shallow water could affect the abundant sea life that lives there, while releasing it too close to the seafloor wouldn't give the mud an opportunity to spread and thin before settling. This could potentially bury the immobile creatures that reside on the bottom at these depths (albeit at very low densities). The Goldilocks plan is to discharge the seawater and mud through a second pipe at an intermediate depth of about 1,200 meters.

Oceanographers from MIT and elsewhere have been studying the environmental consequences of such operations. They even mounted a research expedition in the Pacific in 2018, during which they pumped a mixture of dye and mud from the bottom into the water. This allowed the researchers to discern whether the fine mud particles would glom together. "It doesn't look like that's the case," says E. Eric Adams, an expert in water-quality monitoring at MIT, who was one of the participants in that study. This experiment also helped the scientists to verify their models of the movement of the resulting turbid plumes. "We showed that you could do a fairly good job with a simple equation," says Adams.

Oceanographers will have weeks or months to investigate further how well their models match reality when the Metals Company conducts its 2022 tests with the *Hidden Gem*. Later, Machin says, "we plan to ramp up with bespoke, newly built vessels." That assumes that the company continues to receive the needed permits from the International Seabed Authority, which has jurisdiction in these waters.

There are many examples of seafloor disruption—trawling by fishing vessels, dredging, even the mining of diamonds off the coast of Namibia, to name a few. These actions take place where marine life is far more abundant than at the great depths where nodules form. But given the World Wildlife Fund's call for a moratorium in deep-seabed mining, it's likely the Metals Company's upcoming pilot operations will stir up as much debate as it does mud. ■



A Cool Form of Energy Storage

CRYOGENIC energy-storage company Highview Power will begin operations at its Carrington plant near Manchester, England, this year. Cryogenic energy storage is a long-term method of storing electricity by cooling air until it liquefies (about –196 °C). Crucially, the air is cooled when electricity is cheaper—at night, for example—and then stored until electricity demand peaks. The liquid air is then allowed to boil back into a gas, which drives a turbine to generate electricity. The 50-megawatt/250-megawatt-hour Carrington plant will be Highview Power's first commercial plant using its cryogenic storage technology, dubbed CRYOBattery. Highview Power has said it plans to build a similar plant in Vermont, although it has not specified a timeline yet. —*Michael Koziol*

Illustration by MCKIBILLO

FIRST WIN FOR THE NEURORIGHTS CAMPAIGN CONTINUED FROM PAGE 29

biometric privacy laws around the world and to consider whether those rules apply to the novel technology.

The entrepreneur Bryan Johnson, who founded the Los Angeles-based neurotech company Kernel in 2016, agrees that overzealous regulation is a threat to the young industry. Rafael Yuste "has said that he wants all brain devices to be considered medical devices," Johnson tells *IEEE Spectrum*. "I think that would be a crushing blow to the industry." Johnson says it's already quite hard and expensive to start a brain-tech company that builds devices for consumers or scientists. "I funded this company with $50 million of my own money," he says. If every neurotech device had to clear the regulatory hurdles required of medical devices, such as proving efficacy in large-scale clinical trials, he believes the expense would be crippling.

Kernel is currently selling its first noninvasive brain scanner to neuroscientists, but Johnson says the company will have a consumer product ready in 2024. The company has given a great deal of thought to its privacy policy, Johnson says, which is centered around two principles: Individuals should always provide full consent for how their neural data will be used, and they should always have control of their data. "We all have a shared interest in being good actors here," Johnson says. "If we don't, they're going to come in and regulate us." ■

PLANET-COOLING TESTS COULD START IN 2022 CONTINUED FROM PAGE 49

Engineering, and Medicine last year called for developing "international governance mechanisms" and global scientific partnerships to ensure solar-geoengineering research moves forward in a "socially responsible manner."

Establishing a governing body isn't a guarantee that the interests of wealthy, powerful nations won't overtake those of poorer, more vulnerable countries, notes Jennie C. Stephens, director of Northeastern University's School of Public Policy and Urban Affairs in Boston. She points to existing international efforts, such as those to reduce greenhouse gas emissions or distribute COVID-19 vaccines, that have struggled to balance the needs and desires of disparate populations.

Solar geoengineering is "a very narrow way of looking at the climate crisis," Stephens adds. "All it's thinking about is the physical temperature and the physical system, without thinking about...how different people in the world will be impacted if we were to try to modify and manipulate the Earth's climate system."

AS HARVARD'S BALLOON flight garners both support and scrutiny, parallel research continues in the lab. Earlier iterations of SCoPEx proposed using sulfate particles, which exist in the stratosphere and are known to cause cooling. In 1991, when Mount Pinatubo erupted in the Philippines, it created a haze of particles so dense that it temporarily cooled the planet by about 0.6 °C. But sulfate aerosols—the combination of particles and water—can destroy the planet-protecting ozone layer and also heat up the stratosphere, changing air circulation and weather patterns.

Models suggest that calcium carbonate might be more benign. Calcium carbonate is bountiful in the lower atmosphere, in the form of calcite dust, but it doesn't exist in the stratosphere.

At Columbia University, in New York City, Han Huynh studied the substance as a Ph.D. candidate in V. Faye McNeill's group. For her experiments, Huynh used a glass aerosol flow-tube reactor, coupled with a chemical-ionization mass spectrometer. She measured the reaction between calcite aerosols and hydrogen chloride, a stratospheric trace gas that can, through chain reactions, ultimately impact the stratospheric ozone level. The flow reactor was kept at around −66 °C using a layer of circulated coolant sealed in a vacuum layer and encased in foam. Researchers continuously monitored the number of calcite aerosols, their surface area, and other factors.

Huynh and McNeill recently studied how calcium carbonate could affect global ozone. "What we see is that the uncertainty is really, really high," Huynh says. "There's no way to tell right now, based on our study, whether or not it will have a positive or negative impact." That's largely because not enough is known about calcium carbonate chemistry itself. "You need to continue these lab studies a lot longer before [you can] say, 'OK, this is a good idea. We should go and test this outside.' "

As research continues in the lab and, eventually, outdoors, Frank Keutsch says he's working to expand SCoPEx's team to include scientists from Latin America, Africa, and the Asia-Pacific region. "This global conversation is really important, because people's views on these technological solutions vary drastically across different cultural backgrounds and different areas," he says. "It should be a little bit more diverse than a few people from Harvard." ■

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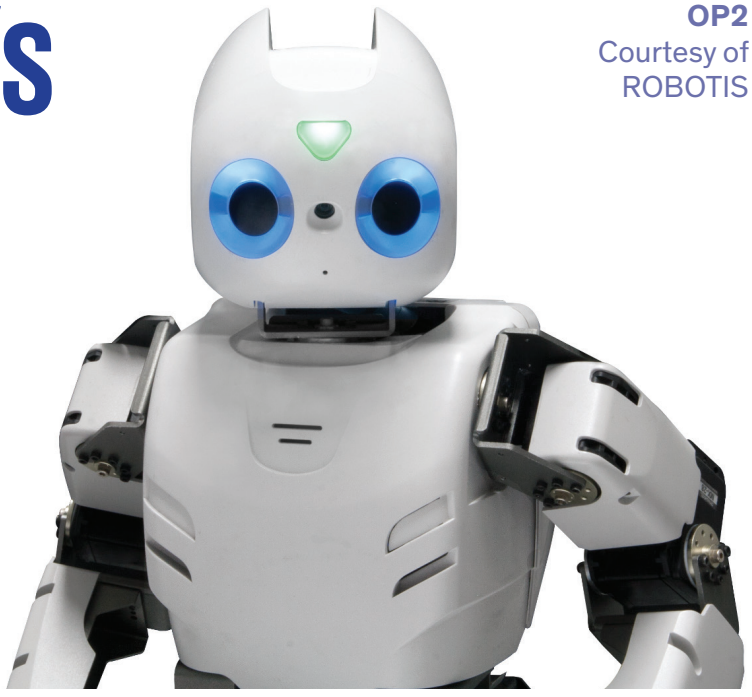

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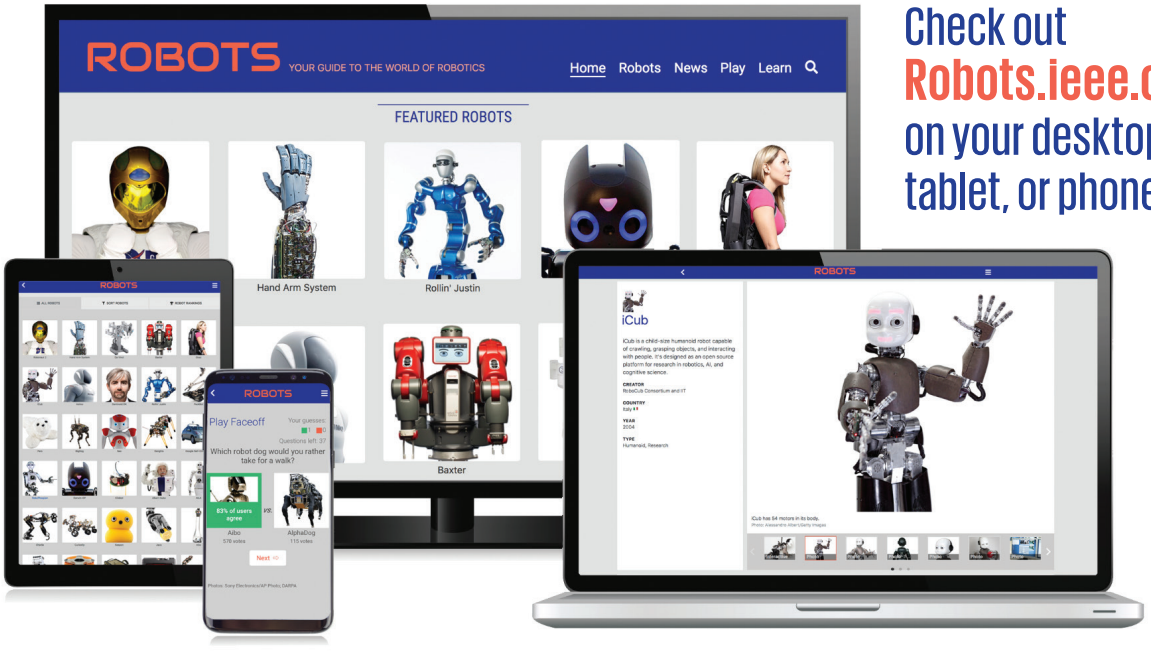

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CASE WESTERN RESERVE UNIVERSITY
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Faculty Position in Electrical Engineering
Department of Electrical, Computer, and Systems Engineering
Case Western Reserve University, Cleveland, Ohio

The Department of Electrical, Computer, and Systems Engineering at Case Western Reserve University (CWRU) invites applications for a tenure-track faculty position in Electrical Engineering at the Assistant Professor level. Appointments will be considered for starting dates as early as **July 1, 2022**. Candidates must have a Ph.D. degree in Electrical Engineering or a related field.

The search is focused in the areas of micro/nanosystems and integrated circuits, with a strong emphasis in applications related to human health and symbiotic integration of humans with machines in wearable and implantable fashion. In micro/nanosystems, the department is looking for candidates with expertise in novel devices, heterogeneous integration, flexible/wearable systems and advanced packaging. In circuits and instrumentation, the department is particularly interested in candidates with expertise in analog/mixed-signal integrated circuits for sensor interfacing. The department is particularly interested in candidates with experience in both focus areas.

Additional information about the position, department, and application package is available at

https://engineering.case.edu/ecse/employment.

CWRU provides reasonable accommodations to applicants with disabilities. Applicants requiring a reasonable accommodation for any part of the application and hiring process should call 216-368-3066.

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Contact Frank Trigueros, trigueros2@llnl.gov

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UAF Electrical and Computer Engineering Faculty Position. The ECE Department and the Geophysical Institute (GI) invite applications for a tenure-track faculty position at the assistant or associate level with specialization in radar, lidar, or small satellite development applied to Space Physics research.

Applicants must have a BS degree in Electrical or Computer Engineering and a PhD in Engineering or a closely related field. The successful candidate will have a strong commitment to undergraduate and graduate teaching and will help strengthen collaborations between the Electrical and Computer Engineering Department and the GI Space Physics and Aeronomy Group.

UAF is a Land, Sea, and Space Grant Institution, Carnegie classified as Doctoral University with high research activity. As a public, regional, comprehensive university, UAF is committed to building a culturally diverse and inclusive organization and strongly encourages women, minorities, individuals with disabilities, and veterans to apply.

Applications are accepted online at **http://careers.alaska.edu Job 518273**. First review of applications will begin on January 24, 2022, but later applicants will continue to be reviewed until the position is filled. Direct questions to Dr. Denise Thorsen, Search Committee Chair, dlthorsen@alaska.edu.

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Assistant Professor - Electrical Engineering
Work Type: Instructional Faculty – Tenured/Tenure-Track
Location: San Luis Obispo, CA

The Electrical Engineering Department in the College of Engineering, California Polytechnic State University, San Luis Obispo, CA, (Cal Poly) invites applications for a full-time, academic year, tenure-track faculty position at the Assistant Professor rank in the following areas:

- Modern Wireless/Digital Communications
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Responsibilities include, but are not limited to: (a) teaching undergraduate classes and laboratories in electrical engineering in general as well as graduate courses in an area of specialization. The ability to teach courses in more than one sub-specialty is preferred; (b) supervising undergraduate and graduate-level research; (c) developing and maintaining externally-funded research programs; (d) collaborating with other faculty on curricular, research and professional development interests; (e) engaging in activities related to service in the form of student club advising, curriculum development, and shared governance.

For additional information, including required and preferred qualifications, please visit:

https://jobs.calpoly.edu/en-us/job/506623/assistant-professor-electrical-engineering

https://ee.calpoly.edu/

The projected start date is September 12, 2022, for the 2022-2023 AY. Review of applications will begin in January, 2022.

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Faculty Positions in ECE

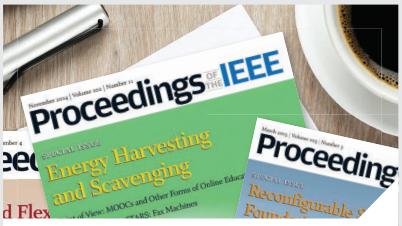
The Department of Electrical and Computer Engineering (ECE) at North South University (NSU) invites applications for several faculty positions at the rank of Professor, Associate Professor, and Assistant Professor. The depart-ment is interested in candidates with proven track record in education and research in the areas of algorithms, artificial intelligence, robotics, big data, cybersecurity, database systems, distributed systems, power systems, control engineering, communication systems, and signal processing. Candidates must have a Ph.D. degree in the related field. The review of the applications will begin on 1 January 2022, and continue until filled.

Established in 1992, NSU is the first and top ranked private university in Bangladesh. NSU is ranked 215 in QS Asia University Rankings 2022 and the ECE department's program is ranked among 601-650 in QS World University Rankings by Subject 2021 in Computer Science and Information Systems.

To apply, please send your application with cover letter and copies of supporting documents to **vicechancellor@northsouth.edu**

Department of Electrical and Computer Engineering, North South University, Dhaka, Bangladesh.

Phone: +880-2-55668200 Extension: 1527
Contact email: atiqun.noor@northsouth.edu



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The Department of Electrical and Computer Engineering, University of Victoria, invites applications for two Assistant Professors with eligibility for tenure in the areas of power electronics, electrical power systems, renewable energy systems, and/or electrical machines and drives.

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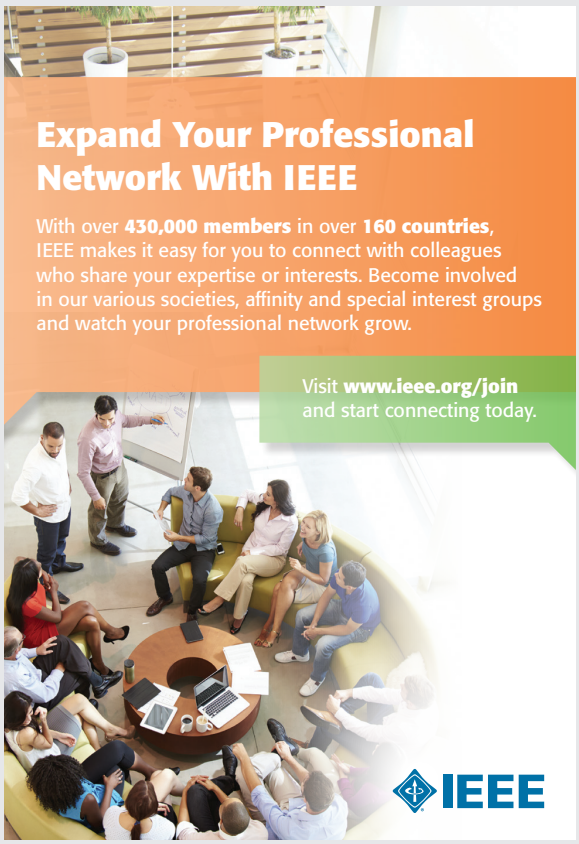

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Applications are invited for:

Department of Mechanical and Automation Engineering

Professor(s) / Associate Professor(s) / Assistant Professor(s) *(Ref: 210002DC)*

The Chinese University of Hong Kong (CUHK) is ranked one of the top 50 universities worldwide according to the QS and THE World University Rankings of 2021/22. It is also named the Most Innovative University in Hong Kong by Thomson Reuters in four consecutive years (2016-19). In the 2020 Research Assessment Exercise, 100% of our impact cases achieved the highest rating 4*, meaning "outstanding impacts in terms of their reach and significance". The overall quality in mechanical and production engineering of CUHK is also the highest, up to 94%, among all universities in Hong Kong by adding both categories of 4* (world leading) and 3* (internationally excellent). Further information about the Department is available at http://www.mae.cuhk.edu.hk.

The Department of Mechanical and Automation Engineering (MAE) at CUHK is seeking excellent candidates in the following areas:

- Robotics, in particular with expertise of medical sensors, robot actuators, and soft robotics with connection to the CUHK T Stone Robotics Institute, which focuses its primary research on medical and service robotics through collaboration among experts in engineering, medicine and social science;
- Design and manufacturing: CAD/design optimization and automation; digital manufacturing; and
- Dynamic systems and control.

Applicants should have (i) a PhD degree in Mechanical Engineering or a related discipline; and (ii) a proven record of academic scholarship and high potential for excellence in teaching and research.

The appointees will (a) teach undergraduate and postgraduate courses; (b) develop an externally funded high impact research programme; (c) supervise postgraduate students; and (d) provide service to the Department/Faculty/University, professional organizations and the community.

Similar to tenure tracked positions at universities in USA, appointments will initially be made on contract basis for up to three years initially commencing August 2022, which, subject to mutual agreement, may lead to longer-term appointment or substantiation later. Outstanding candidates with substantial experience for Professor rank may be considered for substantive appointment forthwith. The rank and exact start date will be negotiated with the successful applicants.

[Those who have responded to the previous advertisements for the posts (Refs. 180001TU, 160001CP and 200001GH) are under consideration and need not re-apply in this instance.]

For more information, please contact Ms. YL Kan at ylkan@mae.cuhk.edu.hk.

Application Procedure

Applicants please upload the full resume with a cover letter, copies of academic credentials, publication list with abstracts of selected published papers, details of courses taught and evaluation results (if available), a research plan, a teaching statement, together with names, addresses and e-mail addresses of three to five referees for providing references.

The University only accepts and considers applications submitted online for the post above. For more information and to apply online, please visit http://career.cuhk.edu.hk.

THREE (3) PROFESSORS IN THE INRS–UQO JOINT RESEARCH UNIT-CYBERSECURITY SECTOR (AP 21143)

Énergie Matériaux Télécommunications Research Centre (EMT)
Three Tenure-track Position

Context and summary

The INRS Énergie Matériaux Télécommunications Research Centre (EMT) is seeking to fill three new tenure-track professor positions as part of the Joint Research Unit between INRS and University of Québec in Outaouais (UQO), with a strong potential for transferring knowledge and technology to users in the cybersecurity sector.

The INRS is a graduate-level research university that has consistently ranked #1 in Canada for its research intensity. The Énergie Matériaux Télécommunications Research Centre brings together world-renowned telecommunications experts in digital technology development and other fields. UQO has been active in cybersecurity for 20 years with its computer security research lab and cybersecurity graduate training, which is being expanded into a bachelor's program in cybersecurity.

The INRS-UQO Joint Research Unit in Cybersecurity is located on UQO's Gatineau campus, near the National Capital Region, and is part of Connexité, Gatineau's innovation zone designed to spur technological and social innovation in the fields of cybersecurity, digital identity, and digital wellness.

Main duties and responsibilities

- The three new professors are expected to conduct state-of-the-art research in cybersecurity related topics and may teach courses in these programs;
- Though these postings are essentially focused on research, experience in teaching will be considered an asset, as will be teaching of cybersecurity related courses.

Requirements

- Candidates are anticipated to have a PhD in computer science, electrical engineering, computer engineering, or a related field;
- They will need to demonstrate their potential to build an original and funded research program in the field of cybersecurity;
- Candidates must also demonstrate how they can utilize their expertise to strengthen collaborative research with existing faculty at the EMT Research Centre and UQO;
- Candidates with the following (non-exclusive) fields of expertise are being sought: privacy and data security; cyber-physical systems and embedded systems security; IoT, blockchain, and cloud/fog computing security; cybersecurity, artificial intelligence, and autonomous cybersecurity systems; and quantum and post-quantum cryptography;
- Applicants in other fields of cybersecurity are strongly encouraged to apply.;
- Hiring is foreseen at the Assistant Professor level, but candidates at the Associate Professor level will also be considered.

Working language

The working language at both INRS and UQO is French. Fluency in English is required.

Candidates whose native language is not French are encouraged to apply. The Centre will provide them with all the resources necessary to facilitate their learning of the French language.

Workplace

UQO Gatineau Campus
283 boulevard Alexandre-Taché, P.O. Box 1250, Station Hull
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Salary

In accordance with the collective agreement in effect at INRS.

How to apply

For more information on the positions and to apply, please visit: https://inrs.ca/en/jobs/three-3-professors-in-the-inrs-uqo-joint-research-unit-cybersecurity-sector-21143/

Applicants should submit a i) brief letter of interest, ii) a 3-page statement of research accomplishments in the field of cybersecurity and goals for future research, including potential collaborations with existing INRS-EMT and UQO faculty, iii) a full CV, iv) a statement of teaching and supervision experience and philosophy, and v) the names and contact information of three references. The deadline to apply is **February 15, 2022** and interviews will be held shortly thereafter.

Incomplete applications will not be considered.

Any additional documents that cannot be transmitted electronically but are necessary to complete your application should be sent by mail to the following address:

Director
Institut national de la recherche scientifique (INRS)
Énergie Matériaux Télécommunications Research Centre
1650 Lionel-Boulet Blvd., Varennes (Quebec) J3X 1S2 CANADA

INRS Institut national de la recherche scientifique

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UNIVERSITY OF NORTH CAROLINA CHARLOTTE

Tenure Track Faculty Positions

The UNC Charlotte Department of Electrical and Computer Engineering (ECE) invites applications for three tenure-track Assistant Professor positions starting from Fall 2022. Candidates with strong academic records and research interests in all areas of ECE are encouraged to apply with particular interest in the following:

(a) AI and imaging (Position #004378): Core areas of expertise include signal and image processing, computer vision, machine learning, AI, autonomous systems, and related areas.

(b) Communication networks (Position #004414): Core areas include computer networks, mobile and wireless networks, with special interests in current and emerging topics such as IoT, 5G networks and beyond, machine learning for communications, networking infrastructure for smart cities, software defined networks, and related areas.

(c) Devices and systems (Position #004453): Core areas of interests include electronic, optoelectronic, power electronic, electromagnetic, nanoscale devices and systems. Applicants with synergistic potential in related areas are also encouraged to apply.

Candidates should be committed to excellence in teaching at the undergraduate and graduate levels, development of sponsored research programs, supervision of student research, student mentoring, and academic services. Priority will be given to candidates having original and promising research as demonstrated by peer-reviewed publications, potential for success in extramural funding, and a plan for future research that integrates well with existing department strengths and the ability to contribute to diversity initiatives. A Ph.D. degree in Electrical or Computer Engineering or equivalent is required by the time of contract.

The ECE department offers B.S. and M.S. degrees in both Electrical Engineering and Computer Engineering, and Ph.D. degrees in Electrical Engineering, with approximately 700 undergraduate and 175 graduate students; see **http://ece.uncc.edu** The ECE Department currently comprises 33 full time faculty members who are actively engaged in research and teaching in the broad areas of computer systems, communications, controls, signal/image processing, electronics devices, and power and energy systems.

Applications must be made electronically at **http://jobs.charlotte.edu/** for Position #004378 (AI and imaging), Position #004414 (communication networks), or Position #004453 (devices and systems). Applicants should submit a complete resume/curriculum vitae, a cover letter/letter of intent, a statement of teaching and research experience/goals, and contact information of at least three references. Review of applications will begin immediately, and the position will remain open until filled. Women and minority candidates are encouraged to apply. Candidates having demonstrated ability to contribute to diversity initiatives are encouraged to apply.

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Past Forward

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Ode to the Envoy

The Motorola Envoy was a handheld device that heralded nearly every basic function of today's smartphones. Unveiled in 1994, the Envoy featured an icon-filled home screen depicting an old-school office desk, complete with telephone (a landline, of course), Rolodex, notepad, and calendar; a wall clock, in- and out-boxes, and filing cabinet completed the scene. In the graphical user interface, which ran on the innovative Magic Cap operating system, each icon linked to its associated application. By intuitively integrating numerous functions on a single device, the Envoy prepared its users for the eventual arrival of the smartphone. ■

FOR MORE ON THE HISTORY OF THE MOTOROLA ENVOY, SEE spectrum.ieee.org/pastforward-jan2022

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